Assessment of HVAC Systems Design and Operation For Indoor Air Quality in Saudi Arabia

by

Raza Ahmed Khan

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

ARCHITECTURAL ENGINEERING

May, 2000

Assessment of HVAC Systems Design and Operation for Indoor Air Quality in Saudi Arabia

BY

Raza Ahmed Khan

A Thesis Presented to the

DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the

Requirements for the Degree of

MASTER OF SCIENCE

In

ARCHITECTURAL ENGINEERING

May 2000

UMI Number: 1401868

Bell & Howell Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS
DHAHRAN 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

This thesis, written by

Raza Ahmed Khan

under the direction of his thesis advisor and approved by his thesis committee, has been presented to and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN ARCHITECTURAL ENGINEERING

Thesis Committee

Dr. Ismail M. Budaiwi
Chairman

Dr. Ahmet Z. Sahin
Member

Dr. Mohammad S. Al-Homoud
Member

Dr. Ismail M. Budaiwi
Department Chairman

Dr. Abdallah M. Al-Shehri
Dean of Graduate Studies

16/9/2000
Date

Affectionately dedicated
to

MY LOVING
Mother, Father,
Brother and Sister

ACKNOWLEDGMENTS

All the praises and thanks be to ***Almighty Allah*** *(SWT), the Lord of the worlds, who gave me the courage and patience to accomplish this work. May the peace and blessings of Allah be upon* ***Prophet Muhammad*** *(PBUH), his family, and his companions.*

My heartfelt thanks and gratefulness to my ***father. mother. brother.*** *and* ***sister*** *for their constant prayers, guidance, encouragement and support throughout my life. They are the source of inspiration to me. Praise be to Allah for bestowing upon me such a loving family.*

Acknowledgement is due to ***King Fahd University of Petroleum and Minerals*** *for providing facilities and support to this research.*

I would like to express deep appreciation and gratitude to my thesis advisor ***Dr. Ismail M. Budaiwi,*** *for his constant help, guidance and the countless hours of devotion throughout the course of this work. He has always been kind, understanding and sympathetic to me. Thanks are due to my thesis committee members* ***Dr. Mohammad S. Al-Homoud*** *(Architectural Engineering Dept.) and* ***Dr. Ahmet Z. Sahin*** *(Mechanical Engineering Dept.) for their interest, cooperation, comments and constructive criticism.*

I would like to thank all my teachers for enlightening me with the education. I am indebted to ***Dr. Adel A. Abdou*** *for his advice and help that he rendered during my studies at KFUPM. I applaud* ***Mr. Iqbal Ghani,*** *department secretary and* ***Mr. Sardar Sharieff,*** *lab engineer at the Building Science Lab for their concern and help.*

Thanks are also due to my friends and colleagues for making my stay at KFUPM a memorable and pleasant experience. Special thanks to my friends ***Mansoor Baig, Mukarram Ali, Iqbal Basha, Jahangir Pasha, Jalal Shah*** *and* ***Khurshid Alam*** *for helping me in data collection and instrument measurements. Equally, I am thankful to friends* ***Syed Intesaruddin, Siddiq Ali, Mohsin Siddiqui, Younus Ahmed, Syed Mazharuddin,*** *and* ***Ahsan Siddiqui*** *for their suggestions and motivation.*

Finally, I acknowledge and appreciate all those individuals, manufacturers, suppliers, consultants, contractors, and building owners, who participated in this research by providing data, product literature, manuals, and feedback.

Raza Ahmed Khan
May, 2000.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

THESIS ABSTRACT

NAME OF STUDENT	:	RAZA AHMED KHAN
TITLE OF THE STUDY	:	ASSESSMENT OF HVAC SYSTEMS DESIGN AND OPERATION FOR IAQ IN SAUDI ARABIA
MAJOR FIELD	:	ARCHITECTURAL ENGINEERING
DATE OF DEGREE	:	MAY 2000

This thesis presents the investigation procedure and results of the assessment of the impact of HVAC system's design and operation on IAQ in commercial and office buildings in the Eastern Province of Saudi Arabia. The research methodology has been designed based on the literature review and includes HVAC designer's survey, building assessment survey, data analysis, and finally, formulating conclusions and recommendations. The HVAC designer's survey consisted of personal interviews and questionnaire survey to the professionals in the field. The questions included dealt with the designer's background information, HVAC systems design and selection, indoor conditions and ventilation design, and HVAC systems components design. A total of 32 HVAC designers participated in the study thereby providing information regarding the IAQ concerns that are taken into consideration. Manufacturers and suppliers of HVAC systems were also contacted to obtain product literature. The most common types of HVAC systems being employed in commercial buildings in this region have been found to be rooftop package units, split systems, and central constant volume systems.

Building survey consisted of identifying the prospective buildings, walk-through inspections, environmental measurements, and questionnaire survey to building occupants. A total of 24 commercial and office buildings were finally selected for this study based on the type of HVAC system employed, the size of the building, and the ease of accessibility. In all, 504 filled in questionnaires were received from the occupants of these buildings. A "Building Assessment" form was developed for the building audit and/or walk-through inspection. Parameters that are indicative of human comfort in spaces such as temperature, relative humidity and carbon dioxide concentration were measured. The outcome of this survey has indicated that most of the buildings do not have a serious problem with IAQ, where as cigarette smoking has been suggested as the main issue of concern to building occupants. Based upon the literature review, the outcome from the analyses of the two questionnaires, and the environmental measurements, general guidelines have been formulated for HVAC systems design, and Operation & Maintenance for improved IAQ in hot and humid climates of Saudi Arabia. An easy to use checklist was developed for the evaluation of HVAC systems design and Operation & Maintenance to insure proper IAQ requirements.

MASTER OF SCIENCE DEGREE
KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS
Dhahran, Saudi Arabia
May 2000

ملخص الرسالة

اسم الطالب	:	رضا أحمد خان
عنوان الرسالة	:	تقييم اعتبارات جودة الهواء الداخلي في تصميم وصيانة وتشغيل أنظمة التكييف والتهوية في المملكة العربية السعودية
التخصص	:	هندسة معمارية
تاريخ الشهادة	:	مايو ٢٠٠٠

تبحث الرسالة في الاعتبارات الخاصة لجودة الهواء عند تصميم وتشغيل أنظمة التكييف والتهوية في المملكة العربية السعودية. فقد تم استقصاء تأثير تصميم وتشغيل وصيانة أنظمة التهوية والتكييف على جودة الهواء الداخلي في المباني التجارية والمكتبية في المنطقة الشرقية من المملكة العربية السعودية. طريقة البحث تمت صياغتها بناء على مراجعة ما نشر سابقا في هذا الصدد، كما اشتمل البحث على مسح لمصممي أنظمة التهوية و التكييف ، ومسح لتقييم جودة الهواء في المباني ، وتحليل البيانات وصياغة نتائج وتوصيات الدراسة. مسح مصممي أنظمة التهوية والتكييف اشتمل على المقابلات الشخصية واستبيانات المختصين في المجال. الأسئلة التي طرحت تعلقت بخلفياتهم وبتصميم واختيار أنظمة التهوية والتكييف وتحديد المعايير التصميمية للبيئة الداخلية وكذلك تصميم أنظمة التهوية والتكييف المختلفة . وقد ساهم في الدراسة ٣٢ من مصممي أنظمة التهوية والتكييف في المنطقة الشرقية. كما تم الاتصال بمصنعي وموردي أنظمة التهوية و التكييف للحصول على المواصفات والمعلومات الخاصة بالمنتج . وقد تبين أن وحدات الأسطح و الأنظمة المنفصلة "سبليت"و الأنظمة المركزية ذات حجم الهواء الثابت هي الأكثر استخداما في المباني المشار إليها.

أما المسح الخاص بالمباني فقد تم بداية تحديد واختيار عدد من المباني للفحص الميداني والقياسات البيئية ومن ثم توزيع استبانة لمستخدمي هذه المباني لمعرفة مدى رضاهم عن البيئة الداخلية التي يعملون بها . فقد تم اختيار عدد ٢٤ مبنى من المباني التجارية والمكتبية لهذه الدراسة بناء على نوع نظام التكييف المستخدم وحجم المبنى وسهولة الوصول إلى المكان. وتم استلام ٥٠٤ استبانة من مستخدمي تلك المباني . بالإضافة إلى ذلك فقد تم تطوير نموذج لتقييم المباني تم استخدامه للمعاينة خلال المسح الميداني. كما تم قياس درجة الحرارة والرطوبة النسبية وتركيز ثاني أكسيد الكربون حيث تعتبر مؤشرات هامة لمدى راحة الإنسان في الأمكنة المختارة. وقد أوضحت نتائج هذا المسح أن معظم المباني لا تعاني من مشاكل كبيرة في جودة الهواء بينما تبين أن دخان السجائر هو مشكلة أساسية ويعتبر الهاجس الأساسي بالنسبة لمستخدمي تلك المباني.و بناء على مراجعة الدراسات السابقة ونتائج تحليل الاستبيانين والقياسات البيئية ، تمت صياغة إرشادات عامة لتصميم وتشغيل وصيانة أنظمة التهوية والتكييف للحصول على بيئة داخلية جيدة في إطار الأجواء المناخية الحارة الرطبة السائدة. كما تم تطوير نموذج سهل الاستخدام لمراجعة العوامل الأساسية المساعدة على تحقيق جودة هواء داخلي عالية عند تصميم وتشغيل وصيانة أنظمة التكييف والتهوية.

درجة الماجستير في العلوم
جامعة الملك فهد للبترول والمعادن
الظهران- المملكة العربية السعودية
مايو ٢٠٠٠

CHAPTER 1

INTRODUCTION

1.1 Background

Ever since humans have inhabited this planet, they have sought to protect themselves from exposure to harsh weather conditions. Early man thus found refuge in naturally occurring shelters such as caves and thick bushes in forests. Slowly he began to develop his habitat with the aim of achieving greater security and comfort. The advancement in science and technology paved the way for the most sophisticated enclosures that were more comfortable and secure than ever before.

Now, many people spend most of their time indoors where the climate is artificially controlled to achieve the required thermal, acoustical, and visual comfort, in addition to the acceptable indoor air quality (IAQ) conditions. Earlier, IAQ was merely an issue of concern related to odor. But, in the 1990's it has become an area of great interest because of its profound impact on the occupant's health and productivity. More recently, it has been declared as American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE's) one of the top research categories with an allocation of 20% of the total research budget in its 1999-2000 research plan. The funds were approved at the ASHRAE 1998 annual meeting (ASHRAE Insights, Sept. 1998).

Good IAQ is an important component of a pleasant and productive indoor environment. Occupants of buildings with air quality problems suffer from symptoms like eye, nose and throat irritation, dry skin and mucous membranes. fatigue, headache, wheezing, nausea and dizziness resulting in discomfort (Sterling et al., 1993). Most of these symptoms disappear after leaving that particular place. This leads to increased absenteeism. reduced performance and lower productivity. The relationship between human health and indoor air quality is an area of current concern and study for many researchers around the world. IAQ has become a pervasive problem plaguing the building industry worldwide. Poor IAQ in buildings is primarily related to new building technology. new materials and equipment and energy management operating systems.

Acceptable IAQ is defined in the ASHRAE standard 62-1989 as "air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80 percent or more) of the people exposed do not express dissatisfaction". This means that health considerations must be made along with the human comfort. Eventually buildings were classified as healthy and sick. A building is known as sick when more than 20% of its occupants exhibit any of the varied symptoms for more than two weeks and the symptoms disappear after leaving the building.

The air supplied through the air-conditioning system is increasingly becoming the only means to dilute indoor-generated pollutants, as the building envelope is growing tighter to meet requirements of energy efficient buildings.

This has resulted in much less air leakage to naturally dilute indoor-generated contaminants and more reliance on HVAC systems. This indoor air needs to be evaluated and its impact on human health is studied for the welfare of occupants.

In order to enhance the comfort and well being of the occupants. indoor environments have been controlled with extensive and often complicated heating, ventilating and air-conditioning (HVAC) systems. The primary purpose of these systems in a building is to regulate the dry-bulb air temperature. humidity and air quality by adding or removing heat energy. These systems employ filtration, water. air currents and mechanical & electrical devices which may accumulate organic dusts or microorganisms that become a source of bioaerosols which if inhaled may induce disease on an irritant. toxic or immunologic basis (Jordan, 1998). Most IAQ problems are the result of one of the three sources: (a) outside air dampers have failed or have been over-ridden to save energy (b) indoor air pollutants overcome ventilation rates (c) outside air can be polluted or contaminated (Int-Hout, 1993).

Research conducted by federal agencies in North America has identified the source of IAQ problems to be malfunctioning, poorly maintained, or inadequately designed heating ventilating and air conditioning systems. The findings of the extensive investigation that were carried out to diagnose and mitigate IAQ problems concluded that the main factors are the inadequate ventilation, indoor generated contaminants, infiltration of outdoor contaminants and contamination from the building fabric and materials (Sterling et al., 1993).

There are various types of HVAC systems with different mechanical design and applications. Some of the most common types include the single zone system, variable air volume (VAV) system, fan coils and individual units. These systems can also be classified as central air-conditioning systems, packaged systems, split systems and window type systems. The changes in the design of HVAC systems so as to meet comfort needs, energy conservation and to reduce maintenance cost may result in HVAC systems becoming reservoirs and sources of the problems related to IAQ. However proper design, commissioning and operation & maintenance of these systems could be vital to avoid these problems.

Concerns over IAQ have driven it to the forefront of work place problems for the 1990s. Health, economic and legal matters associated with IAQ seem destined to make it a dominant problem for developers, owners and managers of commercial and institutional properties well into the next century (Hansen, 1991). This has resulted in making the engineer's and facility manager's jobs more difficult and has put the owner at greater risk.

Indoor environment in general and IAQ issues in particular, has not been a prime concern for research in Saudi Arabia (Al-Qahtani, 1993). In response to the global awareness for improved productivity and healthier occupants, it is high time that measures must be considered by the kingdom to investigate the quality of indoor spaces. Since most buildings are built airtight and dependent on

HVAC system to maintain their indoor environment comfortable. the impact of HVAC systems on IAQ needs to be investigated.

1.2 Statement of the Problem

HVAC systems are used to control the comfort conditions in the buildings with regard to temperature, humidity, odor, air distribution and ventilation. These systems serve as the lungs of the building and the occupant's health depends on the effectiveness of these systems to a large extent. It has to be properly designed and maintained in order to avoid the IAQ related problems. In Saudi Arabia. harsh climatic conditions have made it necessary to use HVAC systems to control the indoor climate of buildings in order to create a comfortable and productive environment. Most part of the year is considerably hot necessitating the constant use of air-conditioners. Almost all buildings are air-conditioned. employing some kind of HVAC system to control temperature. humidity. odor. air quality and ventilation.

Researchers have indicated HVAC-related inadequacies to be the primary cause of most IAQ problems (Sterling et al., 1993). These problems could arise because of the deficiency in HVAC system design, maintenance, operation. controls, air balancing, and occupancy related issues (Tamblyn. 1992). Various studies have established that the HVAC system is responsible for 50 to 60 percent of building generated IAQ problems, and it is capable of resolving up to 80 percent of these problems. This means that if a building is "sick", chances are the HVAC system is at fault, or can remedy the problem. The design, operation and maintenance of HVAC system is therefore at the heart of IAQ improvement program (Hansen, 1991).

IAQ problems could arise in several ways, like for example, the outdoor contaminants can find their way into a building along with the fresh air or from one space to another within the same building via re-circulated air. Other problems could be linked to deficiencies in the HVAC system, such as uncalibrated controls, inoperable equipment, or inadequate maintenance and operating practices (EPA, 1998). Hence the HVAC system could be either a distributor or a source of pollutants.

In recent years, much importance has been given to energy conservation. As a result, energy efficient systems became popular, most of which compromise with the air quality. One of the popular techniques that have been adopted globally for energy conservation is the reduction in the rate of ventilation. Thus the outdoor air for controlling contaminant concentration is not available in sufficient amount thereby creating IAQ problems. The impact of such strategies on Saudi Arabian commercial buildings is not known and needs investigation.

1.3 Significance of the Study

IAQ is vital to public health, their performance and productivity. The problem is real and it is not going to go away by itself. U.S. army research findings have suggested that IAQ related health problems are costing an estimated $15 billion a year in direct medical costs and about 150 million lost workdays (Hansen, 1991). Concerns regarding health, productivity, absenteeism, vacant facilities and the threat of lawsuits are destined to make IAQ the dominant issue for building owners and facility operators through the 1990s.

Since the exploration of oil in the Kingdom, there has been a great change in the living conditions of the people. Consequently, new air-tight and air-conditioned buildings replaced old constructions. And now almost all buildings are air-conditioned. Therefore, proper design, operation and maintenance of HVAC systems is an essential component in solving the IAQ problems. These problems could be addressed by adequate design of ventilation & air distribution, filtration, and proper operation & maintenance strategies. In contrast, HVAC systems could create a problem by circulating the contaminated outdoor air or by aiding in the microbial growth, and it could also solve the problem by the provision of adequate fresh air ventilation rate or through proper maintenance of the system.

In Saudi Arabia, limited research has been conducted in the field of IAQ and indoor environment, and hence this study will be directed to the evaluation and improvement of indoor space conditions, thereby paving the way for productive and healthier environments. The whole world has given prompt attention to this serious problem, and the developed world has geared up to identify strategies for solving these problems. As a result professional societies and associations like ASHRAE have established various standards and guidelines to eradicate IAQ problems. It is due time for Saudi Arabia to act swiftly and join the international awareness against polluted indoor spaces. It is important to know the design practices of HVAC designers and the operation practices of maintenance personnel for the well being of the community, as it is directly related to health and attitude of the occupants.

1.4 Objectives of the Study

The main objectives of this research study are:

1. To get familiarized with the HVAC systems design practices pertaining to IAQ in Saudi Arabia.
2. To quantitatively and qualitatively assess indoor air quality status in commercial and office buildings
3. To assess the operation and maintenance practices of HVAC systems that affect IAQ and identify related sources of IAQ problems.
4. To recommend strategies and guidelines for the proper design, operation and maintenance of the HVAC systems for better IAQ.

1.5 Scope and Limitations

This study will give the first look to design practices and operation strategies of HVAC systems in Saudi Arabia, and their intimate relationship to the quality of indoor air. Guidelines and recommendations have been suggested based on available knowledge in literature and the results from analyzing questionnaire surveys, as well as on-hand experience from site walkthroughs and measurements.

The study is limited to hot-humid climates represented by the Eastern Province of Saudi Arabia. Its results are limited to commercial buildings of this region because of the local weather conditions and HVAC design practices. Also the number of buildings investigated is limited due to accessibility reasons.

1.6 Research Methodology

This section describes the general methodology adopted for the investigation of the IAQ problems that are related to the HVAC systems. The evaluative strategies and protocols that have been used by various investigators show a general consistency and commonality in approach. All these strategies recognize the need to employ a multidisciplinary approach to the evaluation of IAQ problems (Collett, et al. 1993).

Hence, a multidisciplinary approach was adopted to achieve the objectives of the study. The approach included information regarding the physical status of the building, the HVAC systems and controls, the type and extent of occupant health and comfort concerns, the objective quality of air, the occupant's subjective perceptions of comfort in their environment, and the HVAC design practices for commercial and office buildings in the Eastern Province of Saudi Arabia.

The main sources of collecting the information for this research are through extensive literature review, questionnaires & interviews with HVAC designers, review of engineering drawings, walk-through the selected buildings, visual inspection, questionnaires & interviews with the building occupants, interaction with maintenance & operation personnel, and field measurements of certain environmental parameters that are indicative of air quality and comfort conditions in spaces. Figure 1.1 illustrates the flowchart of various components involved in this research methodology. It was planned and carried out in different phases. These phases includes the extensive literature review on the subject, followed by the HVAC designers' survey and interaction with the manufacturers and suppliers of HVAC systems. The next phases consisted of the occupant's survey and field measurements. Finally, analysis of the collected information has been carried out and recommendations proposed for improving indoor air conditions.

1.6.1 Phase 1: Literature Review

Extensive review of literature has been carried out to acquire the in-depth understanding of the issues related to indoor air quality and the HVAC systems. This provided a sound background for the exploration of various problems that are associated with the topic in the Kingdom of Saudi Arabia. This exercise was of immense help in designing the strategy of research in general, and formulating the questionnaires in particular. Many articles from various journals and books have been referred to in the literature review section, a majority of which has been published by ASHRAE.

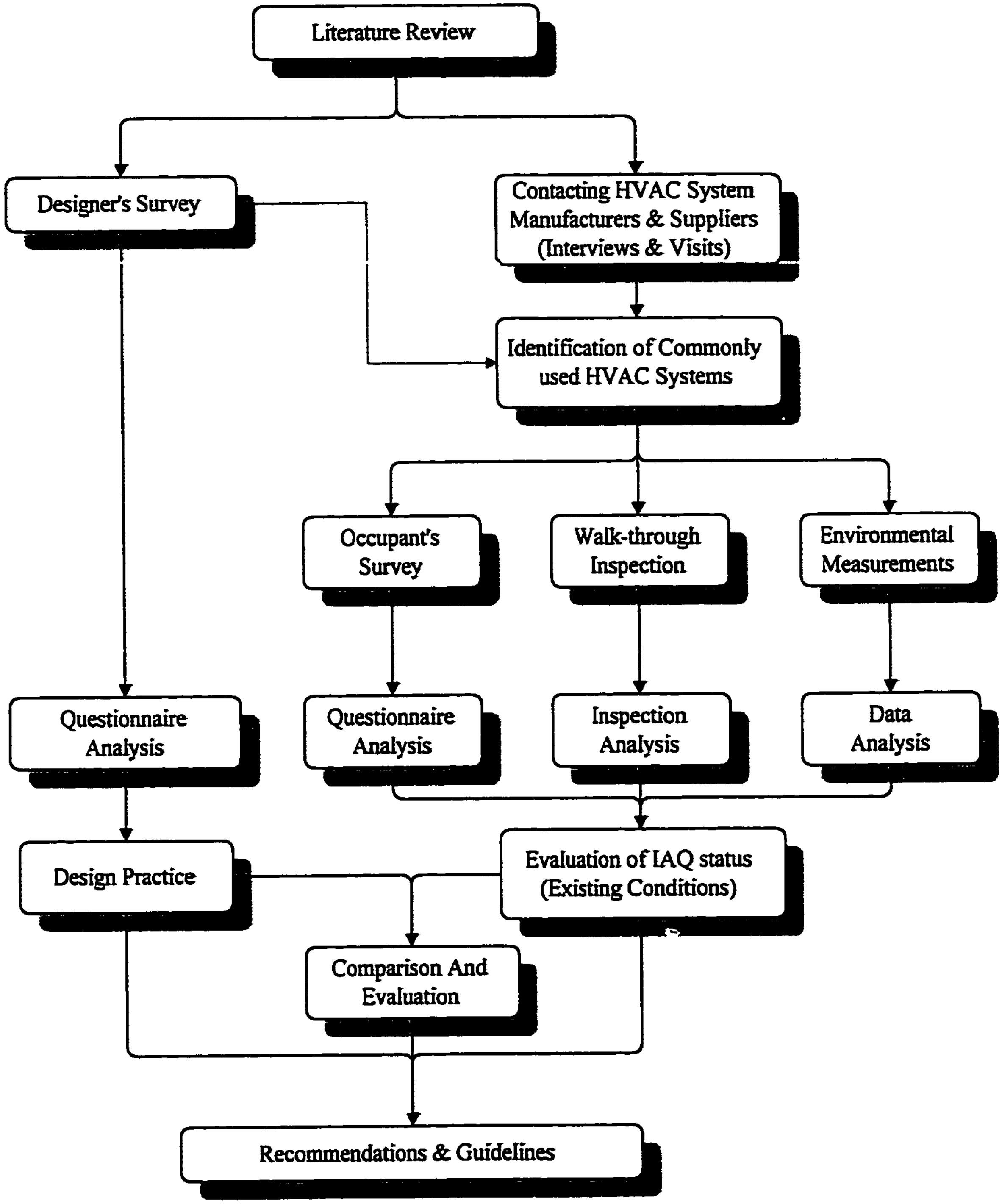


Figure 1.1: Research Methodology Flowchart

1.6.2 Phase 2: HVAC Designers' Survey

The next step towards the investigation of the problem was the interaction with HVAC design practitioners in the Eastern Province of Saudi Arabia. Self-administered questionnaire surveys and personal interviews with the designers were carried out which provided useful information. Several aspects of design and compliance with guidelines were also discussed during personal meetings. The architectural and engineering plans of the investigated buildings were reviewed, wherever possible, to have a glance at their design practice. Various manufacturers and suppliers of HVAC systems were contacted and information obtained through informal interviews and discussions. Their information along with the designers' feedback, was useful in identifying the most common types of HVAC systems that are employed in commercial and office buildings.

1.6.3 Phase 3: Building Survey

The next phase was the identification of certain office and commercial buildings to be studied in the Eastern Province of Saudi Arabia. Simple walk through inspections have been conducted to identify pollutant sources within and adjacent to the building, to inspect the operational conditions of the HVAC systems and to observe other general characteristics of the occupied space. Reviews of architectural and engineering drawings were also done whenever available. Self-administered questionnaires and interviews were carried out with the occupants of investigated buildings. The intensity of the problem was assessed through field measurements. The following parameters have been measured to assess the air quality as affected by the HVAC system: temperature, relative humidity, and carbon dioxide. These parameters have been measured at four different locations. These locations are (a) near the supply diffuser, (b) near the return diffuser, (c) a central location in the room, and (d) a location near the outside air intake.

1.6.4 Phase 4: Data Analysis

Detailed analyses of the designers' questionnaire, occupant's questionnaire, visual inspection form, and field measurement parameters have been conducted in the following chapters. The analysis of the designers' questionnaire has helped to obtain a clear picture of the HVAC design practices. The existing condition of commercial buildings in terms of HVAC system's performance and its impact on IAQ were established as a result of occupant's survey and field measurements.

1.6.5 Phase 5: Conclusions and Recommendations

Finally, the results of analysis of the designers' questionnaire and the existing conditions of buildings were compared and evaluated to reach meaningful conclusions. Strategies have been recommended to mitigate the HVAC system's design-related IAQ problems and to improve the operational and maintenance practices of those systems to rectify and improve the quality of indoor air.

In other words, it could be stated that the study has been carried out in two main stages. Firstly, information was gathered from the HVAC design professionals to know about the design practices in this part of the world. Secondly, feedback from the building occupants and data from the instrument measurements was integrated to know the existing conditions of IAQ in buildings and the performance of HVAC systems.

A structured approach to IAQ investigation that integrates field measurements with feedback of occupants could be used as a long-term solution to the problem of monitoring IAQ variability in modern office buildings (Vischer, 1993).

CHAPTER 2

LITERATURE REVIEW

The purpose of air-conditioning is to create a comfortable and healthy indoor environment. Creating and monitoring comfortable and healthy environment within buildings has been a sustained occupant's requirement and a challenge to HVAC designers and operators. The impact of the quality of indoor environment on the performance, efficiency, quality and morale of individuals are significantly important factors that needs prompt consideration. The main purpose of air-conditioning is to maintain temperature, humidity, air circulation and air quality within an indoor environment. Air-conditioning is defined as "the process of treating air to meet the requirements of a conditioned space by controlling its temperature, humidity, cleanliness, and distribution (ASHRAE, 1989a).

Most new sophisticated buildings have carpeting, furniture, draperies, and other accessories that out-gas a variety of materials, specially volatile organic compounds (VOC's) with potential for harming human health (McQuiston and Parker, 1994). Terms like "sick building syndrome" have been coined and the acronym for IAQ has become a familiar term in HVAC technical literature. "Building-related illness" is another term associated with unhealthy buildings where the cause of the symptom is known.

Although all factors affecting comfort are not fully understood, it is however evident that comfort is influenced by temperature, humidity and air motion as well as thermal radiation from the surrounding surfaces. Also odor, dust and noise effect the perception of being comfortable. A well-designed HVAC system attempts to keep all these variables within specified limits, set by the owner, building codes and sound engineering practice. These complex problems pose a challenge to engineers responsible for the design, construction, and operation of HVAC systems.

2.1 Indoor Air Quality Issues

Indoor air quality is of growing concern in modern airtight buildings. The World Health Organization (WHO) has estimated that 30% of newly built or renovated buildings have IAQ problems or Sick Building Syndrome (SBS). Many reasons have been attributed to this enigma including energy conservation actions such as reduced ventilation, use of synthetic materials in construction, and increasing the levels of outdoor air (Collett, et. al., 1993).

2.1.1 Acceptable Indoor Air Quality

Acceptable indoor air quality is defined as "air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction" (ASHRAE, 1989a). Thus, acceptable IAQ not only ensures the comfort of the occupants, but it also ensures an environment that is free of bothersome dust, odor and harmful levels of contaminants.

Ventilation requirements can be met using either of two procedures: a prescriptive method called the Ventilation Rate Procedure, ad a performance-based method called the Indoor Air Quality Procedure. ASHRAE Standard 62-1989 also specifies basic equipment requirements that include sloped condensate drain pans on cooling coils, cleanable surfaces, and accessibility to all areas of the air conveyance system for inspection and maintenance. It also includes HVAC system installation, commissioning and maintenance issues (Wendl. 1996). Two of the most prominent IAQ challenges from an HVAC system standpoint are controlling the microbial growth and dealing with the increased amount of outdoor air.

2.1.2 Health Issues

The World Health Organization (WHO) defines health as a state of complete physical, mental, and social well being, rather than merely the absence of disability. And hence an adverse health effect is the one that compromises health (Cain. et. al., 1995).

The relationship between human health and IAQ is an area of concern to many researchers. Assessment of health complaints and environmental discomforts related to buildings is carried out by self-administered questionnaires to building occupants prior to building investigation & measurement (Bayers and Black, 1988).

The ASHRAE standard has expressed concern for health in its last three versions. ASHRAE standard 62-1973 recommended ventilation levels to suffice "for the preservation of the occupant's health, safety, and well-being". Its revision i.e., ASHRAE standard 62-1981 stated "to specify indoor air quality and minimum ventilation rates which will be acceptable to human occupants and will not impair health". The last version i.e., ASHRAE standard 62-1989 specifies "to specify minimum ventilation rates and indoor air quality that will be acceptable to human occupants and are intended to avoid adverse health effects".

2.1.3 Sick Building Syndrome

There are many reasons for the contamination of spaces such as human occupancy, materials used in the buildings, furnishings, the space function, and by the introduction of the impure outdoor air. The buildings effected by contaminants that are above the specified accepted levels are known as "sick buildings". Buildings with unusual number of occupants having physical problems have come to be described as having "sick building syndrome" (SBS). The American Thoracic Society recognizes the following as SBS symptoms: eye irritation, headache, throat irritation, recurrent fatigue, chest burning, cough, wheezing, concentration or short-term memory problems, and nasal congestion (Ohman and Eberly, 1998). In addition, the Commission of European

Communities and WHO add skin irritation, such as red or dry skin (Godish, 1995).

The symptoms of SBS are general and are usually associated with the building occupied. SBS has been recognized as a human health problem causing roughly $3 billion in lost annual productivity (Gardner, 1990). The symptoms of SBS are fairly common among the general population, but they seem to be more recurrent in the sick buildings. According to the definition of WHO, 25-30% of office personnel complain of building related symptoms. The symptoms appear during working hours and diminish when the occupants leave the building for weekends or holidays (Lahtinen, et. al., 1998).

Many sources of SBS have been indicated, including inadequate ventilation or thermal control, deficient building design or maintenance, macromolecular organic dust, molecules of biological origin, air borne endotoxins, and other physical, chemical, biological, or psychosocial factors (Ohman and Eberly, 1998).

2.1.4 Contaminants

The contaminants include carbon dioxide, carbon monoxide, other gases and vapors, radioactive materials, microorganisms, viruses, allergens, and suspended particulate matter. These pollutants vary considerably in terms of their classes, levels and sources.

2.1.4.1 Carbon Dioxide

Carbon dioxide is an exhaled byproduct of human metabolism. and for this reason CO_2 levels are normally higher in occupied spaces than for outdoor air. CO_2 level is a major cause of concern with the increase in number of occupants. In many situations, occupant generated CO_2 can serve as a suitable surrogate measure for indoor air quality. The Environmental Protection Agency recommends a maximum level of 1000 ppm (1.8 gm/m^3) for continuous CO_2 exposure, specially for school and residential occupancy, and as a guideline for other building types (McQuiston and Parker. 1994). The measurement of carbon dioxide concentration is utilized for a number of different investigations related to adequate outdoor air supply and distribution within the specific occupied zones of a building, thus making it a powerful IAQ diagnostic tool (Stonier. 1995).

There is a growing evidence that people begin to feel uncomfortable under circumstances in which the CO_2 level surpasses 800 to 1000 ppm (Schultz and Krafthefer, 1993). Measurements of CO_2 in excess of 800 ppm would indicate that less than 25 cfm/person outdoor air was being delivered by the air handling system under the conditions of normal occupancy with light office work, outdoor air is less than 350 ppm and equilibrium conditions have been reached (Stonier, 1995). Exposure of healthy individuals for prolonged periods to 1.5% CO_2 apparently causes mild metabolic stress while exposure to 7-10% will produce unconsciousness within a few minutes (Wadden, et. al., 1983). Odor intensity is one of the indicators of IAQ and is often associated with the level of CO_2 (Gan and Croome. 1994).

2.1.4.2 Carbon Monoxide

Carbon monoxide is a chemical asphyxiant gas. Its affinity for hemoglobin in red blood cells is 200-250 times that of oxygen, which reduces the oxygen carrying capacity significantly (Wadden and Scheff. 1983).

Tobacco smoking and incomplete combustion of hydrocarbon fuels are the two notable sources of carbon monoxide. CO is high in buildings with internal or nearby parking garages. Improperly vented and leaking furnaces. chimneys, water heaters, and incinerators are often the source of problem. CO is a toxic gas, and levels near 15 ppm can affect body chemistry to a large extent. The reaction of humans to different CO levels varies significantly, and the effects can be cumulative. Exposure to CO above their acceptable levels causes headaches and nausea (McQuiston and Parker, 1994).

2.1.4.3 Volatile Organic Compounds

Formaldehyde gas is one of the most common volatile organic compounds (VOCs). Its possible health effects include mucous membrane irritation, asthma, neuropsychological effects and malignant disease. Formaldehyde is used in the production of cosmetics, shampoos, carpets, pressed board, insulations, textiles, paper products, and phenolic plastics. All these products continue to emancipate formaldehyde for long durations, especially in their first year usage. Acceptable limit is 1 ppm as a time weighted 8-hour average (McQuiston and Parker, 1994). Exposure above 50-100 ppm can cause serious injury such as collection of fluid in the lungs, inflammation of the lungs, or death (Wadden and Scheff, 1983).

Solvent encephalopathy is a group of symptoms that are attributed to VOC exposures. "Acute and chronic forms, with headaches, irritability, fine-motor deficits and difficulty concentrating, are the major characteristics" (Burge and Hodgson, 1988). There does not exist any data on the carcinogenic potential in humans for most of the VOCs that are found in the indoor air.

2.1.4.4 Environmental Tobacco Smoke

Environmental tobacco smoke (ETS) is the contamination discharged into the air when the tobacco products burn or when smokers exhale. Breathing in ETS is generally referred to as involuntary or passive smoking. ETS contains a mixture of irritating gases and carcinogenic tar particles. It gives off other contaminants such as sulfur dioxide, ammonia, nitrogen oxides, vinyl chloride, hydrogen cyanide, formaldehyde, radionuclides, benzene and arsenic. It is a known cause of lung cancer and respiratory symptoms, and has been linked to heart disease (Namiesnik, et. al., 1992).

Tobacco smoke particles are particularly hazardous, as they are inhalable (0.1 to 1.0 μm), remain airborne for hours after smoking stops, and attract radon decay products. Passive smoking significantly increases the risk of lung cancer in adults and respiratory illness in children, who live in houses where there are smokers. Apart from these other effects include increases in coughing, wheezing, sputum production, slower lung function growth, and low birthweight babies in mothers who are nonsmokers but are exposed to ETS (Hays, et. al., 1995).

In the United States alone, 60 billion cigarettes are consumed annually by 50 million smokers. Since people spend 90 percent of their time indoors, this means that about 467,000 tons of tobacco is burned indoors each year (Namiesnik, et. al., 1992).

2.1.4.5 Bioaerosols

The term bioaerosol refers to biogenic agents that are airborne. Many bacterial and viral diseases are spread by direct contact between individuals or indirectly as a result of droplets in air which are produced by talking, sneezing and coughing. Apart from these modes of transmission, the diseases can be transmitted through the HVAC system. Infectious agents that are present in outside air can also enter the indoor spaces through these systems.

Biological agents have a serious impact on the maintenance and repair of buildings. The main biological factors causing building related sickness are mould, fungi, bacteria, viruses, protozoa, pollens, house dust mites, insect pests, algae, pigeons and rodents. The source of biological growth within buildings is associated with moisture and the formation of microclimate. Biological pollutants may cause symptoms like stuffy nose, dry throat, chest tightness, lethargy, loss of concentration, blocked, runny or itchy nose, dry skin, watering or itchy eyes or headaches in sensitive people (Singh. 1993). The main concern lies with the children as the General Accounting Office reports that severe indoor air quality problems exist in 15000 U.S. schools, affecting nearly 9 million children (Poruthoor, et. al., 1998).

Legionnaire's disease is a contagious disease that generally occurs as pneumonia. Exposure to contaminated cooling towers, drinking water. cooling systems, and humidifiers are the reasons that have been attributed to its outbreak. Legionella can infect any corner where moisture, temperature and nutrient requirements are met.

The outbreak of infectious diseases such as measles. Q fewer and varicella have been transmitted through ventilation systems. Hypersensitivity diseases are mediated by an immunological response to an antigen or allergen challenge. The two most serious hypersensitivity diseases caused by airborne antigen exposure are asthma and hypersensitivity pneumonitis, which were the results of contamination of ventilation system with bacteria, fungi or protozoan. Humidifier fever is associated with fevers, joints and muscle aches, headaches and fatigue. It is the result of humidification system contamination with microbial growth (Burge and Hodgson, 1988).

There is a growing concern that biological aerosols contribute to the symptoms of SBS. An estimated 5,000 to 7,000 deaths per year are attributed to the Legionnaire's disease in the U.S. and an estimated 3 percent population suffers from asthma.. A study of industrial hygiene parameter measurement at individual work stations, including dust, relative humidity and temperature. demonstrated that respirable suspended particulate, even in the concentration of 30 to 50 $\mu g/m^3$ were strong predictors of complaints on an individual level (Burge and Hodgson. 1988).

2.2 HVAC Systems

HVAC systems are an essential component of modern life, and when properly designed, installed, operated and maintained, provide healthy, comfortable and productive indoor environment. The HVAC system can affect IAQ in the following manner: by the system's ability to transport contaminants generated from sources within and outside the buildings, and by the HVAC system's ability to act as a source of contaminant generation. Thus the system becomes a route through which indoor contaminants are entrained and distributed to the occupied spaces. Increasing outside air for ventilation is not necessarily the solution for solving the IAQ problems, as it could cause a reduction in building occupant comfort (temperature and humidity) due to lack of heating and cooling capacity. HVAC issues related to IAQ are vital for the design of new buildings as well as for renovation of existing ones (Hays, et. al., 1995). The literature verifies that HVAC systems can be sources for some pollutants, although the extent and impact of the problem on human health remains largely unknown (Batterman and Burge, 1995).

Unfortunately IAQ problems have been recognized only after the absenteeism grows, productivity drops, staff is upset, or the tenants have moved out. Then the investigation is started to find the culprit. It is known that HVAC system is responsible for 60 percent of the building generated IAQ problems and has the potential to resolve upto 80 percent of the problems (Hansen, 1991). So, if problem exists relating to IAQ, it is recommended to correct the HVAC first.

2.2.1 Types of HVAC Systems

A variety of HVAC systems are found in commercial buildings that differ from each other according to the building size, occupant activities, building age, geographic location and climatic conditions. ASHRAE has categorized the air-handling unit systems as all-air system, all-water system, air-and-water system, or as packaged unitary equipment systems. The most commonly found systems in Saudi Arabian commercial and office buildings are discussed in the subsequent sections. Familiarity with the components and operations of HVAC systems is essential to diagnose IAQ problems and recommend strategies for redemption. HVAC systems could also be classified according to their energy efficiency as highly efficient, moderately efficient or generally inefficient (Angevine and Fair, 1995).

2.2.1.1 Variable Air Volume (VAV) Systems

It is a type of all-air system, which provide cooling and heating through the air supplied by the system. A fan controller in the air-handling unit compensates for reduced cooling demand in the occupied spaces by reducing the air volume in the system. The airflow is generally regulated through a variable speed controller as shown in Figure 2.1. Pneumatically or electronically powered volume dampers located in duct mounted terminal units control the amount of supply air in the individual spaces.

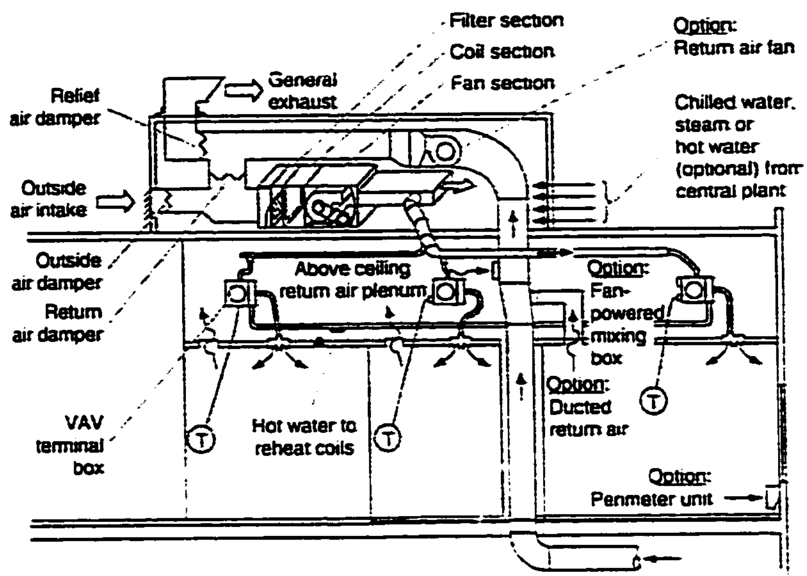


Figure 2.1: Variable Air Volume Air-handling System

(Hays, et. al., 1995)

The chilled water, hot water and steam is provided by the central plant which consists of chillers, boilers and pumps. To maintain a constant supply air temperature at the outlet of cooling coil section, a discharge air sensor controls the cooling coil valve and the operation of outside air and mixed air dampers. The room thermostat will then regulate the reheat coil control valve and the volume damper position to satisfy the room requirements. Economizer cycles are often found on these units.

2.2.1.2 Constant Volume Systems

Single-duct constant volume systems change the supply air temperature in response to the space load while maintaining the constant airflow. This is the simplest of all-air systems that consists of a supply unit serving a single-temperature control zone. The unit could be installed wither within or remote from the space it serves. It could be shut down when not required without affecting the operation of adjacent areas.

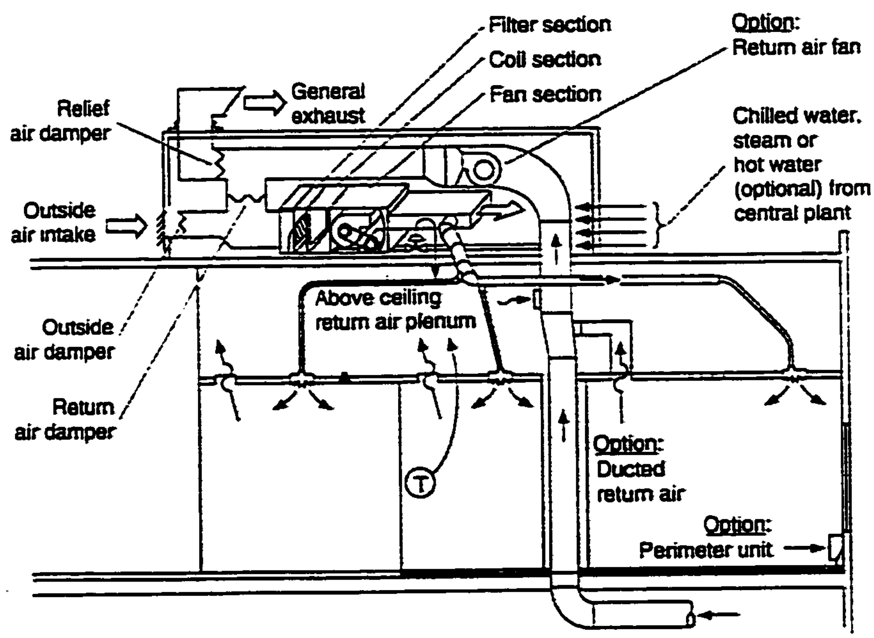


Figure 2.2: Constant Volume Single Zone System
(Hays, et. al., 1995)

Constant volume systems could also be designed as multi-zone systems with or without provision for reheat (Howell, et. al., 1998). It provides more space control for areas of unequal loading. The conditioned air is supplied from a central unit, generally at a fixed cold air temperature, which can be varied so as to reduce the amount of reheat required and the associated energy consumption.

2.2.1.3 Packaged Rooftop Units

Roof mounted package units, shown in Figure 2.3, are one of the prominent types of HVAC systems in small commercial and office buildings. Their lower equipment and installation cost make them popular. The cooling coil in these units is a direct expansion refrigerant coil. The condensation unit section of the packaged units contains the air-cooled condenser and the compressor.

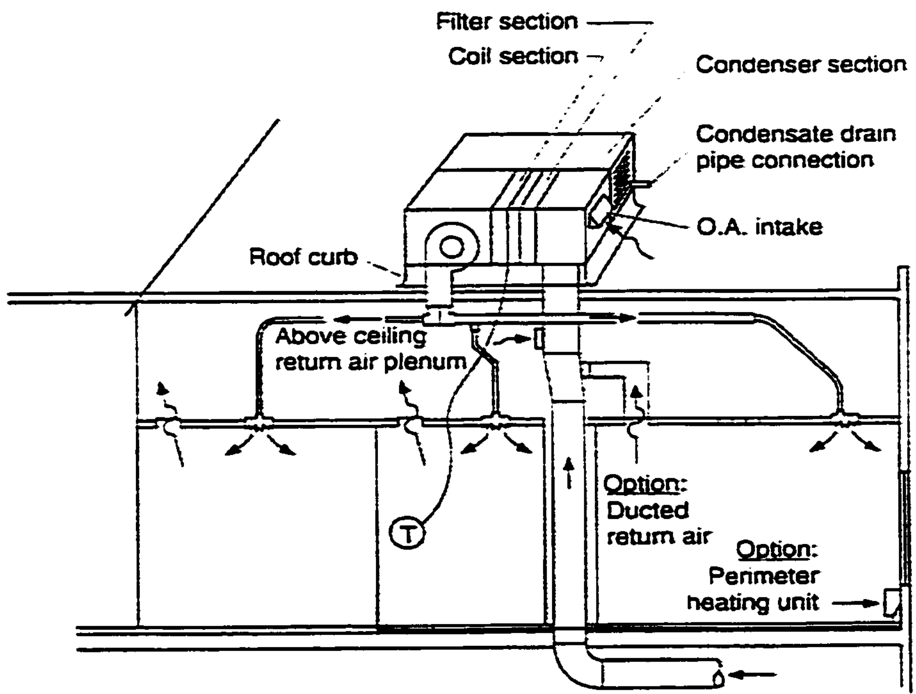


Figure 2.3: Rooftop Packaged Unit

(Hays, et. al., 1995)

2.2.1.4 Split Systems

As the name indicates, these systems are "split" into two, the air-handling units located inside the building and the condensing units located outside, as shown in Figure 2.4. Generally, air-cooled condensing units are used in the Eastern Province of Saudi Arabia. These systems are very popular in low-rise commercial buildings because of their lower cost and ease of installation. These systems may operate with or without distribution ductwork.

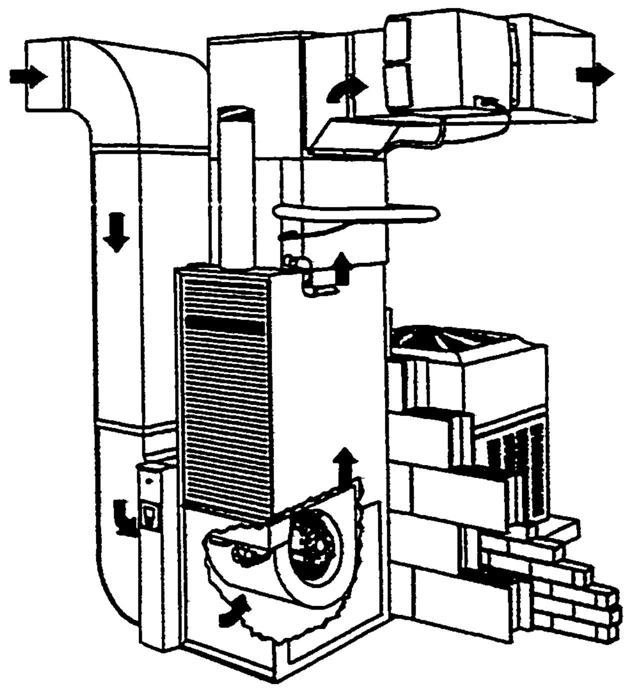


Figure 2.4: Split System
(Howell, et. al., 1998)

2.2.2 HVAC Design

A well-designed HVAC system is an essential component of healthy buildings. Poor design is frequently cited as a primary cause of IAQ problem. The Honeywell IAQ diagnostic team found most of the design difficulties in (a) ventilation and distribution (b) inadequate filtration and (c) maintenance accessibility (Hansen, 1991).

Most of the HVAC systems in use today have been designed in the temperature control era, where IAQ was not at all an issue of concern. And in more recent times, the designers have focussed on energy efficiency and conservation rather than IAQ issues because of the continuous calls for energy-efficient designs. Recently, as IAQ becomes a high stakes game of health, productivity and lawsuits, engineers and architects will be held increasingly responsible for the IAQ the HVAC system delivers. This responsibility is apt to prompt more professionals to stay involved beyond the design stage. Greater accountability and prolonged involvement will inevitably enhance HVAC design.

2.2.3 HVAC Commissioning

Commissioning an HVAC system is not just starting it up after installation and ensuring that the equipment is working. But rather it is a process of building delivery that begins when a project is conceived and ends when the useful life of the resulting structure is over. The ASHRAE Guideline defines commissioning as "the process of achieving, verifying, and documenting a concept through design, construction, and a minimum of one year of operation" (ASHRAE 1989b). A fully functional, fine-tuned HVAC system with complete documentation is the end result of a successfully applied commissioning process.

The ASHRAE Guideline establishes procedures for the HVAC commissioning process for each phase of the project: program phase, design phase, construction phase, acceptance phase, and post-acceptance phase. IAQ concerns should be addressed at each phase of the process to avoid sick building syndrome problems. Based on traditional estimates, the process of commissioning could eliminate as much as half of all IAQ-related complaints. In addition, commissioning process to new and renovated buildings could implicitly eliminate all IAQ related complaints (Sterling, et. al., 1993).

ASHRAE Guideline 1 provides procedures for documenting and verifying the performance of HVAC systems so that the systems operate in conformity with the design intent. Guideline 1 includes procedures for

- Documentation of occupancy requirements and HVAC design assumptions
- Documentation of the design intent for use by contractors, owners, and operators
- Functional performance testing and documentation necessary for evaluating the HVAC systems for acceptance and for adjusting the capability of the design intent (ASHRAE Handbook, 1995).

The process of commissioning takes place continuously from the programming phase through the first year of operation, and touches all parts involved in design, construction, start-up, testing, operation and maintenance. Traditionally, the design teams use to check the physical installation of equipment, and the owner has to rely on the proper installation by the contractor and correct operation as indicated by the vendor's sales literature (Wilkinson, 1999). Now the commissioning process requires that the components and systems are inspected and tested under actual installed conditions.

2.2.4 HVAC Operation and Maintenance

The HVAC has been reported by NIOSH to be the cause of over 50 percent of all IAQ problems and complaints, therefore its maintenance is essential to the operation of healthy building (Hays, et. al., 1995). The lack of trained maintenance personnel or an unsound operations and maintenance policy can be detrimental to the HVAC system's performance and can increase the risk of creating sources of contamination within the HVAC system.

Operation and maintenance departments have inherited the problems of uncommissioned systems in buildings. The lack of time and money spent on commissioning activity has resulted in the delivery of inefficient systems that O&M personnel operate at higher costs for building owners. An effective way to improve the IAQ profile of a building or to maintain good IAQ of a healthy building is to implement a sound HVAC maintenance program. It has been recommended to train personnel of O&M departments, continuously monitor ventilation system and humidity control, moisture control, and periodically test. adjust and rebalance (Burroughs, 1997a).

Poorly maintained ducts can be major problem for indoor air quality. Moisture in the ductwork encourages microbiological growth, which results in building related illness. Fiberglass lined duct work has a very high chance of being affected with microbial growth. The diffusers, metal registers, and perforated grillwork also need regular maintenance. It has to be ensured that the volume dampers within the ducts are working properly for the adequate distribution of air (Hansen, 1991).

An investigation of 51 school buildings in southern Ontario depicted the typical problems found in buildings. A professional engineer reviewed the blueprints of each facility, visited the facility and collected information about the HVAC system, its operation and maintenance. The analysis of the utility data, interviews with the operators and information for the specific HVAC system and controls were used to detect operation, maintenance and controls-related problems. It was found that maintenance and controls-related issues contributed to the major HVAC system problems in buildings. Occurrences of any of the following conditions were classified as maintenance problems requiring immediate action: dirty, blocked screens for air handlers, dirty or malfunctioning humidifiers, dirty filters, high pressure drop, blocked ducts, etc. None of the schools had maintenance documentation for HVAC systems (Tamblyn, 1992).

Six O&M problems that cause inadequate ventilation system economizer operation and overheating have been identified in high rise office buildings. These are negative building pressure, outside air damper closing from freeze stat signal, chillers that are in-operable in winter, improper tracking of supply and return air fans, return air damper malfunction, and HVAC control problems. Proper ventilation system economizer and temperature controls operation and maintenance should be a first priority as it has yield immediate results and proved to be cost effective (Ventresca, 1995).

2.2.5 Ventilation

The process of supplying and removing air by natural or mechanical means to and from any space is known as ventilation. IAQ is dependent on many parameters that include the quality of outdoor air, the design of enclosure, the design of ventilation system, its operation and maintenance, and the presence of sources of pollutants. ASHRAE Standard 62-1989 provides guidelines to deal with all these factors in order to provide an acceptable level of IAQ. The goals of achieving acceptable IAQ and of minimizing energy consumption appear to imply a compromise in this Standard.

Figure 2.5 shows the evolution of ventilation standards since 1900. In 70's and 80's, the emphasis was on the minimum introduction of outdoor air in order to minimize the energy required to treat that air. This trend changed after the implementation of ASHRAE Standard 62-1989. Now most of the buildings are generally operated with outdoor air at 15 to 20 percent of the total supply air.

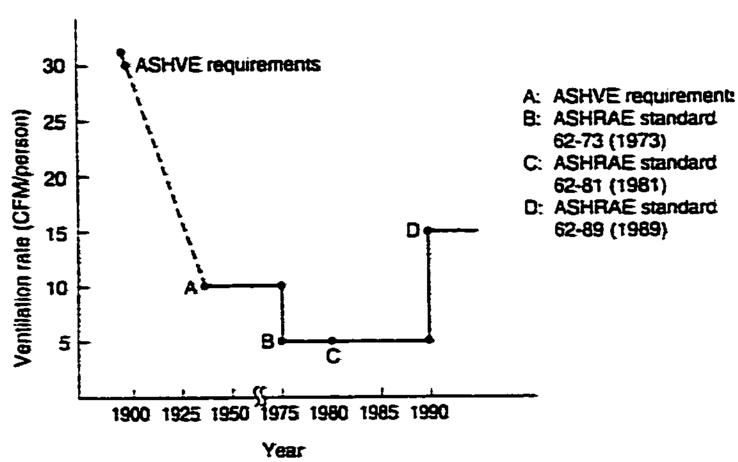


Figure 2.5: History of Ventilation Standards

(Hays, et. al., 1995)

ASHRAE Standard 62-1989 specifies alternative methods to obtain acceptable IAQ:

(i) Ventilation Rate Procedure: acceptable air quality is achieved by providing ventilation air of the specified quality and quantity to the space, or

(ii) Indoor Air Quality Procedure: Acceptable air quality is achieved within the space by controlling known and specifiable contaminants.

Ventilation process uses clean air, often called as fresh air, from outside to dilute the contaminated air of the enclosure. The amount of this outdoor clean air required varies with the type of facility and specific functions. The CO_2 content is a good predictor for the amount of outdoor air required, as the ASHRAE guideline aims to hold CO_2 below 1000 ppm or at 15-20 cfm/occupant in most facilities (McQuiston and Parker, 1994).

When outdoor air is the main source of indoor pollution, mechanical ventilation can be helpful in two ways in controlling IAQ, i.e., by removing pollutants by dilution and through its pressurization effect. A study has been conducted to investigate the contaminant concentration in a single zone enclosure under combined dilution and pressurization effects of ventilation air, when outdoor air is the main source of contamination, using an airflow model in conjunction with an IAQ model. Results from this study are indicative of the appreciable impact of ventilation air pressurization on controlling contaminant concentration (Budaiwi, 1998).

Ventilation efficiency is a term used to describe the ability of ventilation system to distribute supply air and remove the polluted air. Researchers are presently studying ways to measure ventilation efficiency and interpret the results of those measurements. The odors and contaminants can be isolated with the effective design and operation of the HVAC systems, so that pressure relationship inside spaces is controlled. Local exhaust can remove the pollutants before they scatter into the indoor air. Restrooms, kitchen, storage rooms, printing rooms and science labs are some of the examples where local exhaust is essential. Local exhaust helps to prevent the migration of contaminants from strong point sources to other areas (Thompson, 1998). The effectiveness of dilution ventilation in controlling environmental tobacco smoke in office workplace has been carried out in Richmond, North America (Sterling, et. al., 1996). The conclusion was that an outdoor air ventilation rate of 20 cfm per person controlled tracers of ETS exposure to acceptable levels under conditions of moderate smoking activity.

ASHRAE as exercised jurisdiction over IAQ because engineers have important roles in the design, actualization and the operation of systems that could control the indoor environment. The ventilation rate procedure has served reasonably adequately because of its simplicity. But there are liabilities of inflexibility, blindness to unanticipated sources of contaminants and significant variations in rates of emissions. Where as the indoor air quality procedure which is a contaminant based procedure has had little use because of complexity of applications. However it has assets of flexibility in management of indoor air, and source control (Cain. et. al., 1995).

2.2.6 Filtration

The outside air that is required to replenish the oxygen and dilute the pollutants needs to be filtered to free it from the outdoor pollutants and particulate matter. Also the recirculated air needs to be filtered to clean it from the indoor-generated contaminants. Providing an efficient cleaning system is often the final step in assuring that HVAC system will provide healthy and clean indoor environment.

Air pollution control is discussed in ASHRAE Handbook, HVAC Systems and Equipment (ASHRAE, 1992). Contaminants can be eliminated either by absorption, physical adsorption, chemisorption, catalysis or combustion. Because of the variety of suspended particles in outdoor air as well as indoor air, in terms of their size and shape, it is impossible to design one type of air particulate cleaner.

The performance of air filters depends on the size, shape, specific gravity, concentration and electrical properties of aerosols. The operating characteristics of particulate air cleaner depend on factors such as efficiency, airflow resistance and dust holding capacity. The influencing factor for filter design and selection is the degree of air cleanliness desired (McQuiston and Parker, 1994).

Air cleaners play an important role in improving the indoor air quality by restricting the motion of contaminants. To achieve better results, it has to be adequately designed, operated and maintained. There are two main classes of indoor air cleaners: in-duct and room air cleaners. In-duct cleaners are installed within the HVAC systems. The particles are removed by either fibrous filtration, electrostatic precipitation, or electrostatically augmented filtration. Carbon filters are used for organic vapors (Sparks, 1988).

Generally filtration remains an under-utilized technology in the field of IAQ in commercial buildings. Air cleaning can result in valuable and cost effective tactics to achieve and maintain an acceptable environment. It is the responsibility of the design team to take aggressive step to fully utilize the potential of filtration (Burroughs, 1997b).

2.2.7 Temperature

Temperature is often overlooked with regard to its impact on IAQ, however its effect on occupant's comfort is well known. A good HVAC investigation of buildings with IAQ problems should begin with measurements and questions related to temperature and humidity conditions (Hays, et. al., 1995). ASHRAE Standard 55-1992, Thermal Environmental Conditions for Human Occupancy, presents guidelines that are intended to achieve thermal conditions that at least 80% of the occupants would find acceptable or comfortable.

ASHRAE standards specify the range of temperature in which a normal human being feels comfortable as illustrated in Figure 2.6. It is dependent on certain factors like the number of occupants, their clothing style, their activity level, the lighting load, and the equipment present. Figure 2.6 shows the acceptable range of operative temperature and humidity for people in typical summer and winter clothing during primarily sedentary activity. The IAQ investigation should take note of changes in any of these factors for the concerned space. The ISO standard and ASHRAE standard 55 have utilized scales of subjective response to describe an occupant's feeling of warmth or cool in a situation (Int-Hout, 1993).

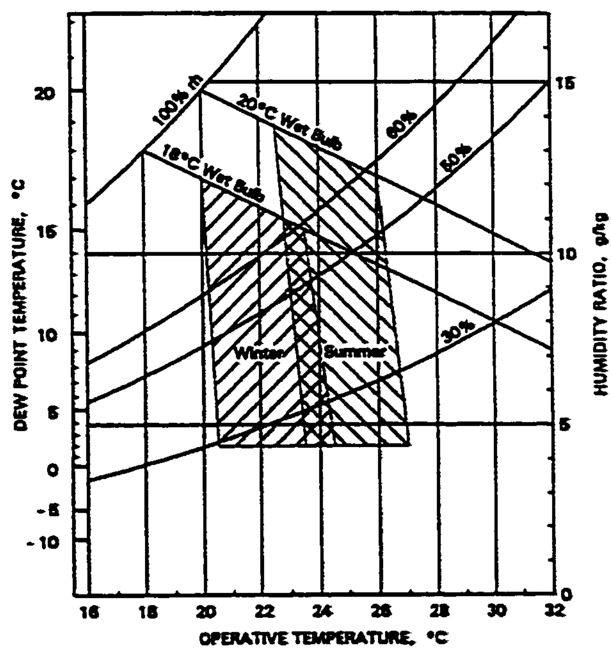


Figure 2.6: ASHRAE Summer and Winter Comfort Zones
(ASHRAE Handbook, 1997 Fundamentals)

Results of an experimental work undertaken to study the impact of room air temperature and relative humidity on materials emission rates indicate that both the temperature and relative humidity have a significant effect on the emissions from paint and varnish (Haghighat and de Bellis, 1998).

Proper air distribution is also essential to ensure comfort conditions. Draft is the local cooling of portions of body caused by poor air distribution. Decreasing air velocity or increasing air temperature could however control it. The layout of air-distribution grilles and diffusers plays a significant role in proper air mixing and temperature control within a space. The thermal sensation depends on the air temperature and velocity in the room (Gan and Croome. 94).

2.2.8 Relative Humidity

Relative humidity is the percentage of moisture in the air relative to the amount it could hold if saturated at the same temperature. It has been proven that humidity adversely affect the health conditions. such as allergies. depending upon the level of humidity. It has been recommended to maintain relative humidity in the range of 30 to 60 percent (ASHRAE. 1992).

Humidity affects our comfort in a number of ways both directly and indirectly. At a certain temperature, decreased humidity results in complaints about dry nose, throat, eyes and skin, typically when the dew point is less than 0°C. Excessive drying of the skin can lead to lesions, skin roughness, discomfort and impair the skin's protective functions. Dusty environments can further exacerbate low humidity dry-skin conditions (Berglund. 1998). Less relative humidity results in dehydrated mucous membranes, sinus irritation, headaches, and other adverse health effects as shown in Figure 2.7 (Hays. et. al.. 1995). ASHRAE Standard 55 specifies that to decrease the possibility of discomfort due to low humidity, dew point temperature in spaces should not be less than 3°C.

More humidity increases the moisture content and aid in microbiological growth. Elevated humidity levels reduce comfort when the skin wetness is above 25%. The discomfort associated with it could be due to the friction between skin and clothing (Berglund, 1998). The effect of humidity on human sensation and health is not well established.

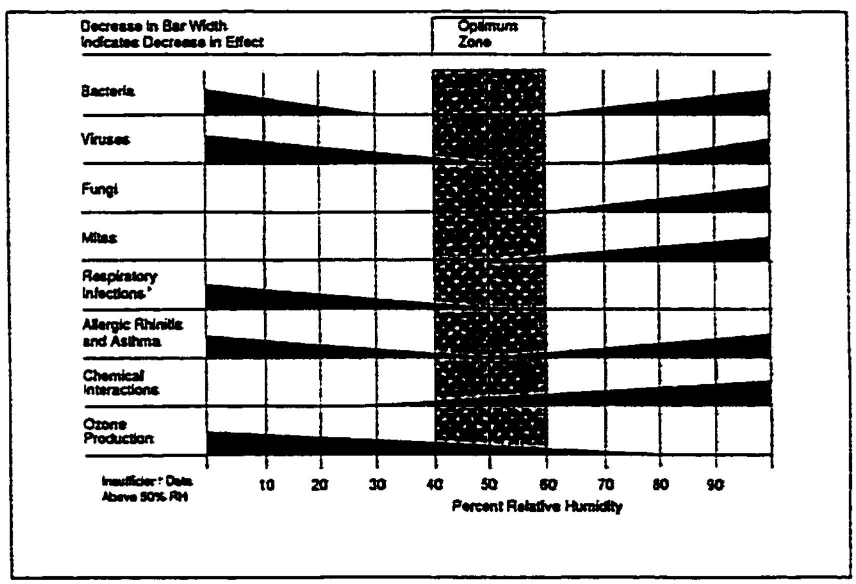


Figure 2.7: Optimum Relative Humidity Range for Health

(Hays, et. al., 1995)

2.3 Investigation of IAQ Problems

The objectives of investigating the IAQ problems are to determine whether an environmental problem exists, to identify the cause of the problem, to cure the problem and to re-evaluate after modifications have been implemented. The field evaluation consists of the following stages (Collett, et. al., 1993):

1. Initial assessment is the first stage in which information is gathered about occupants concerns through meetings with building operators and occupants, review of architectural and engineering plans. and walkthrough inspections.
2. Assessment of occupants is carried out with the help of standard questionnaires wherever there is large population. The results of these surveys could be used to quantify the health & comfort complaints. the impact of demographic differences (age, sex) and psychological factors (stress. satisfaction).
3. IAQ and thermal comfort monitoring is done by measuring five parameters so as to indicate the general performance of HVAC systems. These parameters are carbon dioxide. carbon monoxide. respirable suspended particles, temperature and relative humidity.
4. Follow-up IAQ measurements may include sampling and analysis for formaldehyde, airborne fungi and bacteria, total and specific volatile organic compounds, ozone and nicotine.
5. Ventilation measurements are required to perceive the HVAC system performance. It can be done by airflow measurement to determine flows through the ductwork, supply and exhaust vents.
6. Development and implementation of mitigation strategies should be carried out once the causes of the IAQ problems have been identified. Retrofit actions should be taken to mitigate design-related problems and recommendations should be made to improve the operation and maintenance parameters.

7. Post implementation assessment has to be done to determine the effectiveness of the retrofit actions. Objective measurements of IAQ and thermal parameters can be ideally carried out.

Many practitioners of IAQ evaluation in commercial buildings have developed complementary ways to extract feedback from building occupants so as to determine which environmental parameters should be tested in terms of problems and symptoms experienced by employees. A number of techniques are used ranging from large-scale group surveys to individual interviews. Questions administered to building occupants extent widely in their degree of detail. The information gathered through the occupant survey is accepted to be both valid and reliable. Integration of instrument measurements with occupant feedback can be used as a long-term solution to the problem of monitoring IAQ variability in modern office buildings (Vischer, 1993).

2.4 Case Studies

Case Study I

The building is a large and complex health care facility. As the facility expanded its medical education activities, the Autopsy department took over adjacent office space. No thought was given to the air handling systems configuration, so for several years contaminated air from the autopsy rooms was returned to the general plenum, prior to being redistributed throughout the building. The problem was only identified by chance (O'Sullivan, 1989).

Case Study 2

Water spray humidifiers on air handling supply units achieved humidification for an entertainment complex with several theaters. The building operator didn't drain humidifier pans in the summer, and by July, bacterial growths 3 to 4 in. long were found in each pan. The investigators were not surprised as a stagnant pool of water at room temperature and without chemical treatment provides ideal breeding conditions for bacteria (O'Sullivan, 1989).

Case Study 3

The VA Medical Center in Cincinnati, Ohio, a U.S. government-owned facility embarked on an aggressive energy conservation program because of rising operating cost of HVAC system. The 26,000 cfm delivered to the south wing is split between patient rooms (about 70 percent), general support areas (about 20 percent) and restrooms (about 10 percent). 100 percent of outside air was being used to condition the areas. The design was modified, the conditioned air from this zone is mixed with 4000 cfm of the outside supply air and then routed through the gas-phased filtration system. By cleaning and re-circulating 22,000 cfm, or 85 percent if the air previously exhausted, the hospital realized substantial energy savings with the added benefit of odor removal (Kennedy & Distefano, 1991).

Case Study 4

One of the most extensive surveys carried out to magnify the relationship between IAQ and HVAC is the 1991 Steelcase Worldwide Office Environment

Index. It reports opinions of office workers, tope executives, facilities managers and design professionals in 15 countries, which include the U.S., Canada, Japan and European nations. Without exception, office workers throughout the world perceive poor air quality as a serious hazard. According to the survey, both building managers and designers appear to agree that comfortable heating and air conditioning are not being provided. They also agree that the comfort must be provided by the HVAC systems, possibly for new buildings and renovations (Sterling, et. al., 1993).

Case Study 5

The HVAC system of an elementary school building in Georgia, U.S., was renovated to upgrade the outdoor air ventilation rate and to provide better humidity control. The renovation was a result of numerous indoor air quality complaints and the persistent presence of mold and mildew on interior surfaces. Rooftop HVAC units were being operated intermittently with a ventilation rate of approximately 5 cfm per person. This was modified to 15 cfm per person, and a total energy recovery wheel system was employed to supply the outdoor air and to control relative humidity. Reduction in CO_2 level and other pollutant levels was observed when the HVAC system fans are operated in a continuous mode (Downing and Bayer, 93).

Case Study 6

A study was conducted in a Columbus, Ohio, high-rise office building that was operated with minimum and maximum outside air ventilation. The IAQ complaints were resolved through a comprehensive operation and maintenance assessment, and subsequent improvements. Six problems have been identified related to the operation and maintenance of the ventilation system. They are: negative building pressure, outside air damper closing from freeze stat signal. chillers that are inoperable in winter, improper tracking of supply and return air fans, return air dampers malfunction, and HVAC control problems. Even if these do not resolve the problem completely, it will certainly improve the situation (Ventresca. 1995).

Case Study 7

The climatic data for the western United States consists of high plains and desert. In summer, these areas are influenced by migration of hot, dry air from the interior regions. The use of low temperature supply air systems in this arid climate greatly simplifies the air-conditioning design. The risks associated with moisture migration and sweating of duct are reduced. The introduction of outdoor fresh air becomes far less taxing on the mechanical cooling equipment because of lower enthalpy levels of the dry western climate. Energy costs to assure indoor air quality are lower than for more tropical climates.

Maintaining acceptable indoor humidity levels becomes a major IAQ concern in the arid regions. Coupling an air-to-air heat exchanger to direct evaporative coolers can greatly reduce low temperature supply air refrigeration energy requirements and winter humidification costs while ensuring proper ventilation (Scofield and Des Champs, 1995).

Case Study 8

The research was carried out to assess the effectiveness of the dilution ventilation provisions in ASHRAE Standard 62-1989 in controlling environmental tobacco smoke (ETS) in the office environment. Data was gathered through three interrelated phases: the assessment of the HVAC system performance. personal exposure monitoring of ETS-related constituents, and fixed location monitoring.

The design and operational configurations of the HVAC system were determined form review of mechanical engineering drawings, inspection of HVAC system components and airflow measurements using a micromanometer. Apart from these, continuous monitors for carbon dioxide. temperature and relative humidity were installed at each indoor site and the outside air intakes. This research concluded that the ventilation rate of 20 cfm per person controlled the tracers of ETS exposure to acceptable levels under conditions of moderate smoking (Sterling, et. al., 1996).

Case Study 9

In 1990, Norback et al., investigated 11 SBS buildings in Sweden to study the relationships between SBS symptoms, exposure to environmental factors and personal factors. The study group comprised of a total of 261 employees. SBS symptoms, smoking habits, hyperreactivity, sick leave, work stress, work satisfaction and climate of cooperation at work were assessed by a questionnaire. Chemical and climatological measurements were also carried out in the buildings. The indoor hydrocarbon concentration, hyperreactivity, sick leave and smoking were associated with SBS. The investigators concluded that numerous personal and environmental factors are responsible for the generation of SBS (Lahtinen, et. al., 1998).

Case Study 10

An evaluation of the environmental and thermal performance of a new federal office building in Oregon, U.S. was carried out by the Center for Building Technology, National Institute for Standards and Technology. The environmental parameters that were measured included air infiltration and ventilation rates, building envelope tightness, interzone air movement, detection of envelope thermal deficiencies, envelope thermal resistance, and the levels of indoor contaminants. The air exchange rate was measured using the tracer gas decay method with an automated measuring system. The outdoor air was found to be properly distributed without any signs of short circuiting or poor mixing.

The indoor contaminants measured include CO_2, CO, formaldehyde, radon, VOC and respirable particulate in 0.3-1.0 range. The results indicated that the levels of CO_2, formaldehyde, radon and respirable particles are well within the established guidelines. However, the CO levels were higher because of the airflow from the garage, where the exhaust fan was on automatic mode and was not operating. 37 VOCs in the interior air that seem to be related to the activities occurring inside the building were also reported (Grot, et. al., 1991).

Case Study 11

A field study of the occupant comfort and office thermal environments was conducted in 12 mechanically ventilated buildings in southern Quebec. Canada. These buildings varied greatly in surface area, number of floors. occupant density and building use. A total of 877 subjects were surveyed during hot and cold months. The questions included dealt with health, environmental sensitivity. work area satisfaction, personal control over worker's area, and job satisfaction. The results were compared with the ASHRAE standards. It was found that 56 percent of the occupants rated dissatisfaction with the IAQ at their workstations. Positive relationships were observed between the job satisfaction and satisfaction with office air quality, ventilation, work area temperature (Donnini. G.. et. al.. 1997; Haghighat and Donnini, 1999).

Case Study 12

In 1989, Berglund and Cain concluded that for a subjective evaluation of IAQ, the concentration of pollutants in the air might prove secondary to the influence of temperature and humidity. This surprising conclusion was derived from the subjective responses of 20 subjects studied at three temperatures, three humidities and three activities or metabolic rates. The air was perceived to be fresher and less stuffy with decreasing temperatures and humidity. The effect of temperature was linear and stronger that the effect of humidity. The air quality was uncomfortable when the relative humidity exceeds 50% (Fang, et. al., 1998).

Case Study 13

An investigation of 51 school buildings in Southern Ontario revealed the typical problems found in buildings that received no commissioning. A professional engineer reviewed the blue prints of each facility, visited the site and gathered information about the HVAC system, its operation and maintenance. This information was used to compile a list of building system problems and deficiencies. None of the buildings had complete as-built documentation. and none of them had operating and maintenance documentation for HVAC systems. The operators did not understand the design intent for the system and made sure that the keep the equipment running with minimal complaints. The results of the lack of commissioning effort from an operation and maintenance point of view are: system operation and design problems, comfort and air quality problems. and higher operation and maintenance cost (Tamblyn, 1992).

Case Study 14

To investigate the relationship between construction materials, operating techniques and smoking policies for the improvement of indoor air quality in office buildings, a research study was carried out. Quantitative measurements were recorded in three different specially selected office buildings in Atlanta, Georgia. Building 1, known as "special building" consisted of special construction and furnishing features to minimize the contaminant level. Building 2 was a "control building" was similar to Building 1, but which had been constructed without the special efforts used in Building 1. Building 3 was a complaint building of similar age and had been constructed without special designs to optimize IAQ. The occupants of this building had complained of health symptoms, possibly related to improper air quality. The comparison of indoor environment of the three buildings showed that, in general, IAQ in Building 1 was superior (Bayer and Black, 1988).

Case Study 15

An investigation has been carried out by means of physical measurements combined with a subjective assessment of the indoor environment in a naturally ventilated office room over a period of four months in the winter of 1991-92 at the FURS building of the University of Reading. The study concluded that to achieve a good indoor climate and air quality, it is necessary to supply fresh air either by opening windows or by installing a suitable vent for the introduction of fresh air. The size of the vent opening should ideally be controllable (Croome, et. al., 1992).

2.5 IAQ Studies in Saudi Arabia

2.5.1 Study 1

The Indoor Air Quality problems in Saudi office buildings were investigated by Al-Qahtani (1993). In this study, a sample survey of thirty buildings was undertaken to identify these problems. The survey included two main parts i.e. occupant's survey and building survey. Occupant's survey was carried out to identify the IAQ problems related to the occupants, and the questionnaire consisted of questions regarding the occupant's background, thermal environment, IAQ perception, symptoms, and physical conditions. Building survey was done to investigate IAQ problems related to building systems, and the questionnaire required information regarding operation & maintenance, HVAC system, architectural systems, and indoor environmental related complaints. Thirty buildings were selected and surveyed. A total of 846 occupant's questionnaires were collected.

The results of the study have indicated low IAQ in some of the investigated buildings, which have a negative impact on occupant's health and productivity. It was also observed that the building envelope and HVAC system of buildings have a leading role in maintaining the IAQ (Al-Qahtani, 1993).

2.5.2 Study 2

In another study, quantitative and subjective assessments of IAQ in the 47 buildings of King Fahd University of Petroleum and Mineral (KFUPM), Dhahran, were carried out by Al-Zaharnah (1996). To assess subjectively, an IAQ questionnaire was randomly distributed among a large number of the population of KFUPM. Their responses were analyzed using the 80% satisfaction criteria, which showed that the absolute majority of occupants are satisfied with the IAQ status in their location. Four quantitative IAQ measurement sessions were scheduled, i.e., summer-day, summer-night, winter-day, and winter-night. Five indoor air contaminants were measured. They are formaldehyde (HCHO), carbon dioxide (CO_2), carbon monoxide (CO), sulfur dioxide (SO_2), and total hydrocarbons, in addition to temperature and relative humidity. Summer day measurements recorded the highest concentrations of contaminants and winter nights recorded the lowest contaminant concentration (Al-Zaharnah, 1996).

2.5.3 Study 3

Indoor and outdoor air quality was monitored in thirty selected buildings in Riyadh, the capital of Saudi Arabia, by Al-Rehaili, et. al. (1997). Pollutants monitored were total suspended particulate (TSP), lead (Pb), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO, NO_2), formaldehyde (HCHO), ammonia (NH_3), ozone (O_3), and sulfur dioxide (SO_2). These pollutants were monitored continuously at each site for a period of one week in summer and one week in winter. Indoor temperature and relative humidity were also recorded simultaneously at each of these locations.

A "building data form" was prepared and filled-in by the investigators for each site during the monitoring phase. This accounted for building description, pollution sources, air-conditioning and ventilation practices, and building materials. Another form was developed to get the feedback of the building users in order to elucidate any linkage between the indoor environment and occupant's health and comfort. However, the data collected from building users was not enough to indicate the impact of air pollution on health and comfort. It even did not reflect the variability of indoor pollutant levels recorded during monitoring.

Four measured pollutants that showed normal levels include carbon monoxide, carbon dioxide, ozone and formaldehyde. The other six pollutants were recorded in unacceptable levels. Outdoor pollution sources such as automobiles, power stations, and industrial activities were found to be major sources of indoor and outdoor pollution. Air pollution was observed to be worse in summer than in winter (Al-Rehaili, et. al., 1997).

CHAPTER 3

IAQ CONSIDERATIONS IN HVAC SYSTEMS DESIGN

3.1 Introduction

Design offices are the places where decisions on the performance of buildings are first taken, either good or bad. It is therefore essential to know the considerations that the designers in these offices take into account while designing a building and its systems. Since the study is concerned with the impact of HVAC systems on IAQ, only HVAC designers were approached with the objective of acquiring HVAC related design information. The HVAC systems include all heating, cooling and ventilating equipment serving a building: chillers, cooling towers, air handling units, exhaust fans, ductworks, filters, and associated piping.

3.2 Questionnaire Structure

A questionnaire for HVAC designers (see Appendix B) was developed and administered with the aim of obtaining information on the following aspects of HVAC design practice:

(i) general information like the years of experience, the type of HVAC systems employed, their manufacturer, etc.

(ii) the criteria used for the design and selection of the HVAC systems and their manufacturers

(iii) the range of temperature and relative humidity for designing commercial and office buildings in the Eastern Province of Saudi Arabia.

(iv) the rates of ventilation and fresh air intake considerations

(v) common choices of filters, location and type of duct insulation.

The response to the questionnaire was used to build up a picture of the prevalent design practices in the Eastern Province of Saudi Arabia. Data analysis and discussion of this questionnaire have been performed and are discussed in the subsequent sections.

3.3 Conducting the Survey

The main purpose of the designer's questionnaire is to acquire knowledge regarding HVAC systems design practices and the related IAQ issues that these designers take into consideration while designing commercial and office buildings in the Eastern Province of Saudi Arabia. Many design offices in this region were contacted and persuaded to participate in the study. However, thirty-two designers agreed positively thereby providing cooperation and useful information.

3.3.1 Briefing

The designers were first introduced to the objectives of the study, its scope, and the usefulness of its results. The introduction was accomplished through an introductory document (see Appendix A) followed by a discussion involving the above mentioned aspects of the study. In particular, the need for administration of questionnaire to the design personnel and review of HVAC systems drawings were stressed during these introductory briefings. Designers were convinced that the information will be held in strict confidence and their identity will not be revealed. Furthermore, it was communicated that results of the study would help them know the status of IAQ in buildings in operation. and that recommendations from the study could help them improve future HVAC system's design.

3.3.2 Review of Drawings

Some of the architectural and engineering plans were reviewed at the design offices to analyze the general design practices. The HVAC system drawings were examined to check for load calculations, proper distribution of air, duct layout, fresh air intake, return air plenum, type of HVAC systems, ventilation, exhaust, drain pans, maintenance access, controls, grilles and diffusers.

3.3.3 Personal Interviews

In most of the cases, a personal interview and informal discussion was held along with the questionnaire administration. This helped the designers to come out openly with their design practices. Many real world issues, special cases, problems and their solutions were discussed and shared. All of this was helpful to get an insight into their practice.

3.3.4 Response to the Survey

It was encouraging to observe that the designers appreciated the objectives of the study and promised full cooperation. Most of the designers preferred to discuss the questionnaire and fill it in the presence of the investigator. Others requested for time because of their busy schedule and selected to send the questionnaire through fax. Only a few designers did not respond to the request for participation.

3.4 Questionnaire Analysis

This section presents analysis of the data obtained from the filled questionnaires received from thirty-two respondents. Their responses have been illustrated graphically to have a better understanding of the results.

3.4.1 Background Information

Most of the HVAC designers, who were contacted, possess sound experience in designing HVAC systems in different building types. Almost 84 percent of the designers have more than 5 years of field experience, 53 percent have more than 10 years of experience, and about 34 percent have more than 15 years of working experience. Because of their experience, it could be claimed that the data provided by these designers depict the general design practice. Experience is an important criterion as a new designer may not be well aware of the behavior of various complex components that integrate in any building, or might have not learned lessons from previously accomplished projects. Even the knowledge possessed by a relatively new designer is more theoretical than being practical.

Almost all of the HVAC designers responded to the questionnaire. about 91 percent deal with the design of commercial and office buildings as shown in Figure 3.1. Other major buildings that they design include industrial (about 78 percent) and residential (about 69 percent). 34 percent of them deal with the design of institutional buildings and about 9 percent design other type of buildings. This indicates that most of them have sufficient experience in designing commercial and office buildings.

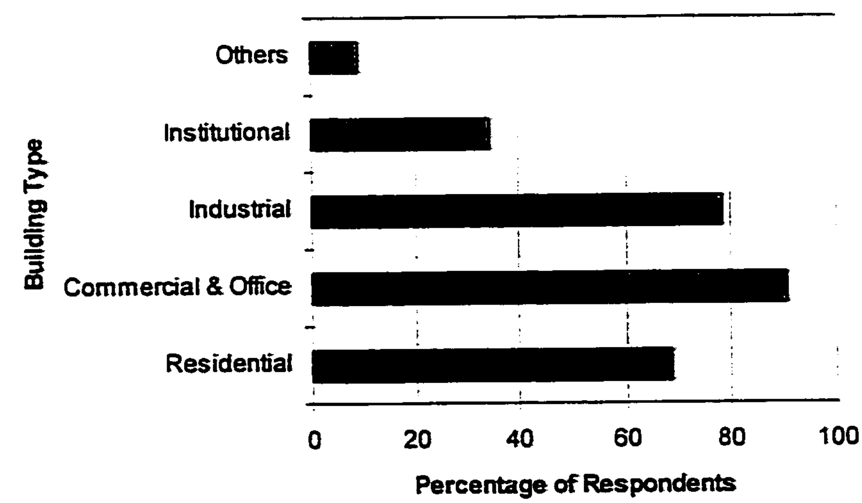


Figure 3.1: Types of Buildings Designed by Surveyed Designers

3.4.2 HVAC Systems Design and Selection

Varieties of HVAC systems are found in commercial buildings. These systems differ according to the size of the building, occupant activities, building age, climatic conditions, geographic location, etc. According to the local designers, the most frequently used HVAC systems for commercial and office buildings in the Eastern Province of Saudi Arabia are the package rooftop units and the split systems as shown in Figure 3.2, with more than 60 percent designers specifying them frequently. In the rooftop package unit, all the refrigeration, cooling, and air handling equipment is assembled together as shown in Figure 2.3. The main difference between the single-zone and packaged system is the absence of central plant for the packaged systems. The cooling coil on the packaged unit is a DX refrigerated coil. The condensing unit of packaged units contains the condenser and the compressor. Rooftop units mostly have an air-cooled type of condenser.

In split systems, the condenser and the compressor are in one package, located outdoors, and the fan and cooling coil are another package located indoors as shown in Figure 2.4. The cooling coil containing the refrigerant joins the indoor unit with the outdoor unit. Generally the split systems employ air-cooled condensing unit. Rooftop package units as well as split systems could be ducted and fresh air could be provided.

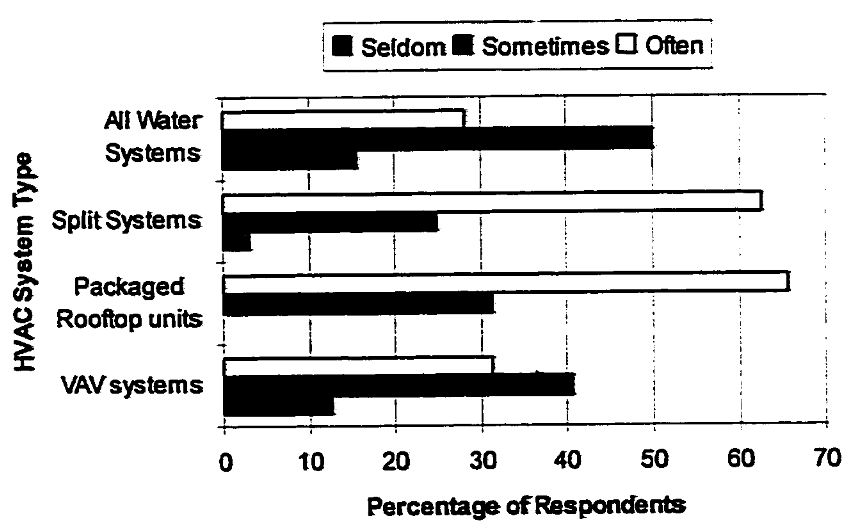


Figure 3.2: HVAC Systems used in Commercial & Office Buildings

Other systems used here are the Variable Air Volume (VAV) system and the Constant Volume (CV) all-air systems. These are the four most widely used systems in the Eastern Province of Saudi Arabia.

The HVAC manufacturers that are popular with the designers for commercial and office buildings are the Carrier, Zamil and Trane air-conditioners, with more than 60 percent designers specifying them frequently as shown in Figure 3.3. York air-conditioner is often specified by about 28 percent of designers and other manufacturers by about 6 percent of designers. All these manufacturers have shown a growing concern for IAQ issues in their product literature and are struggling to provide IAQ friendly products.

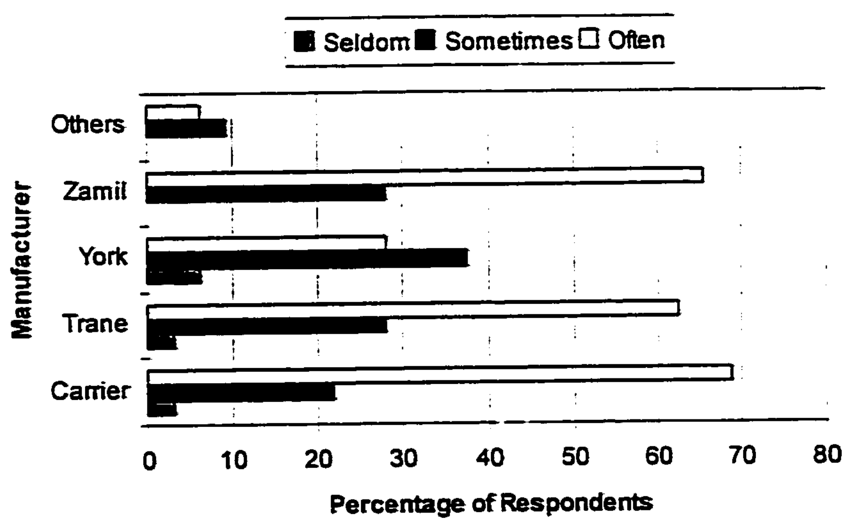


Figure 3.3: Manufacturer of HVAC Systems in Commercial & Office Buildings

According to the designers, the most important criteria for selection of these manufacturers are the suitability for the weather conditions and good experience with the product as shown in the Figure 3.4, with about 69 percent of the designers indicating these factors as their prime concern for selection.

Availability in the market is the next important criteria with about 53 percent of designers specifying it. Around 41 percent of the designers have pointed out that the owner's specification is the main criteria for the selection of the manufacturer. Only about 13 percent of them have other criteria for selection.

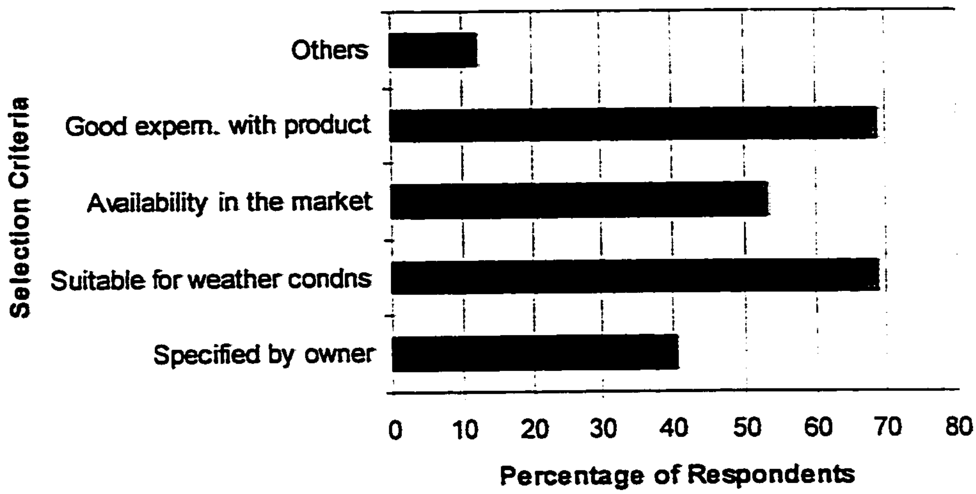


Figure 3.4: Criteria for Selection of the Manufacturer

The main criteria for designing and selecting the HVAC systems is the thermal comfort of the occupants, with about 81 percent of designers indicating it, as shown in Figure 3.5.

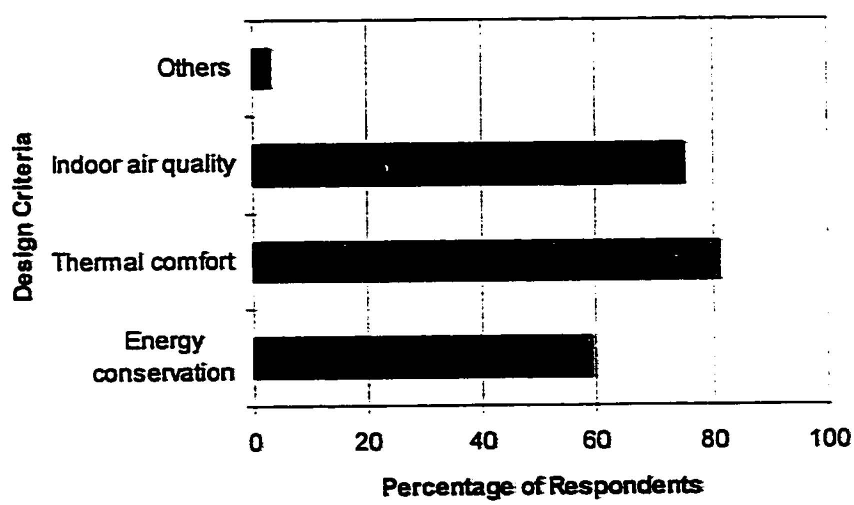


Figure 3.5: Criteria for Designing & Selecting the HVAC Systems

The other criteria are the indoor air quality concerns, with 75 percent, and energy conservation, with 59 percent of designers showing concern.

3.4.3 Indoor Conditions and Ventilation Design

ASHRAE has published Standard 55-1992: Thermal Environmental Conditions for Human Occupancy, which recommends indoor air comfort levels for occupants based upon occupant activity levels and clothing. The impact of temperature and relative humidity on occupant comfort and illness related to their fluctuations is well established. The designer should anticipate, based on the owner's feedback, the occupant activity and equipment, which may reject heat into the environment prior to calculating heating/cooling loads for the HVAC system.

3.4.3.1 Temperature

Standard 55-1992 recommends that the temperature in occupied spaces be maintained between 21°C (70°F) and 26°C (78°F). Temperature is perhaps the single most important criteria that affects the perception of comfort by humans. The most common range of indoor air temperature that the HVAC designers normally design for commercial and office buildings in the Eastern Province is 22°C to 24°C as shown in Figure 3.6. About 69 percent of the designers design in this range. About 28 percent of the designers use the range of 24°C and 26°C, and only about 3 percent of designers use the range of 20°C to 22°C. The design temperature is based on the occupant activities and presence of heat rejecting equipment in the space. Also, the range of design temperature shifts to upper and lower levels of comfort zone depending on the season (summer and winter) and clothing level.

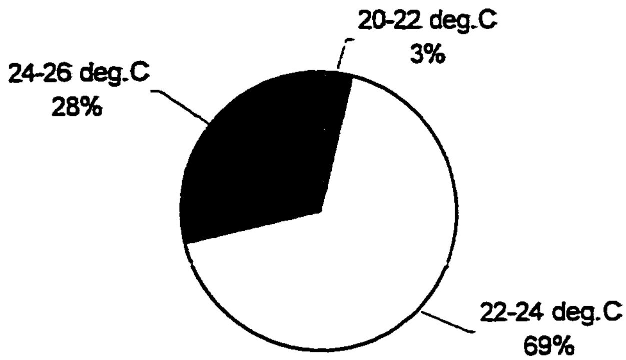


Figure 3.6: Design Range Practices of Indoor Temperature

3.4.3.2 Relative Humidity

Humidity not only affects the subjective feeling of occupants but can cause adverse health conditions, such as allergies, based upon the humidity levels to which they are exposed. ASHRAE Standard 55-1992 recommends that relative humidity in occupied spaces be maintained between 30 and 60 percent. The most common range of relative humidity that the HVAC designers specify for designing commercial and office buildings in the Eastern Province is 50% to 55% as shown in Figure 3.7. About 78 percent of the designers specify this range of relative humidity. This range is the optimum zone of relative humidity, as the bacteria, viruses, fungi and respiratory infections are minimal in this range as shown in Figure 2.7.

Increased humidity levels increases the chances of microbial growth within the spaces where as low humidity levels causes dehydrated mucous membrane, head ache, sinus and other health effects. Approximately 19 percent of the designers specify the range of 45% to 50% of relative humidity for these types of buildings. Only about 3 percent designers specify in the range of 40% to 45% as shown in figure above.

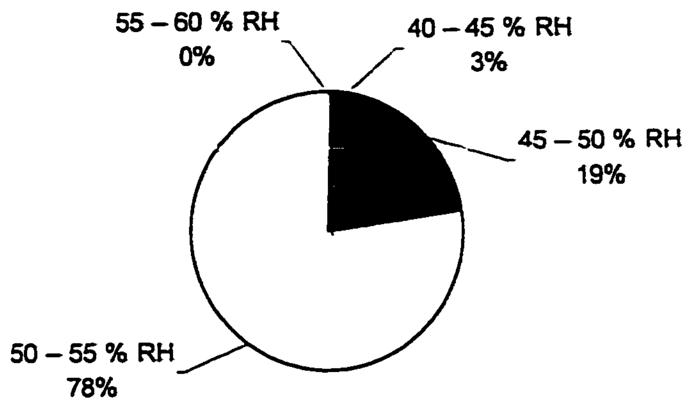


Figure 3.7: Design Range Practices of Relative Humidity

3.4.3.3 Ventilation

Outdoor air or ventilation air is important for HVAC design, as it is a means of controlling indoor air contamination through dilution with fresh outdoor air. ASHRAE Standard 62-1989 is the most widely accepted standard with HVAC design firms in Saudi Arabia, which specifies a minimum ventilation rate of 7 L/s (15 cfm) per person for commercial buildings.

Most of the designers, about 51 percent, specify the ventilation rate of 7-10 L/s (15 to 20 cfm) per person for commercial and office buildings as shown in Figure 3.8. About 34 percent of the designers use a ventilation rate of 5-7 L/s (10 to 15 cfm) per person, where as 9 percent specify a rate of 2-5 L/s (5 to 10 cfm) per person. 6 percent of designers specify either higher or lower ventilation rates than what is discussed above.

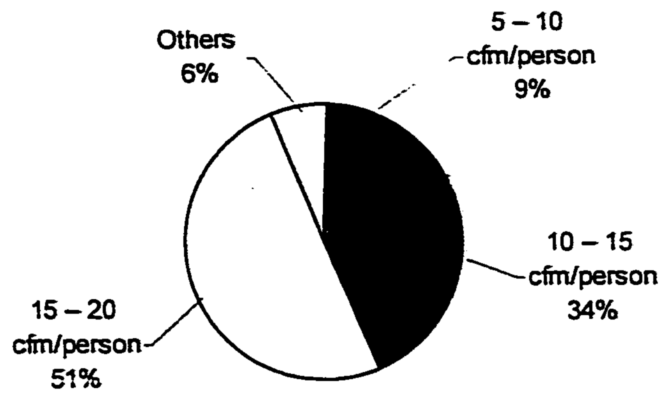


Figure 3.8: Design Ventilation Rate Practices in Commercial & Office Buildings

3.4.4 HVAC System's Components Design

3.4.4.1 Air Filtration

Proper filter selection plays an important role in the control of IAQ. Efficiency, resistance, and dust holding capacity are the main characteristics that distinguish the different types of filters. As shown in Figure 3.9, more than 75 percent of the designers generally recommend and use media filters for commercial and office buildings.

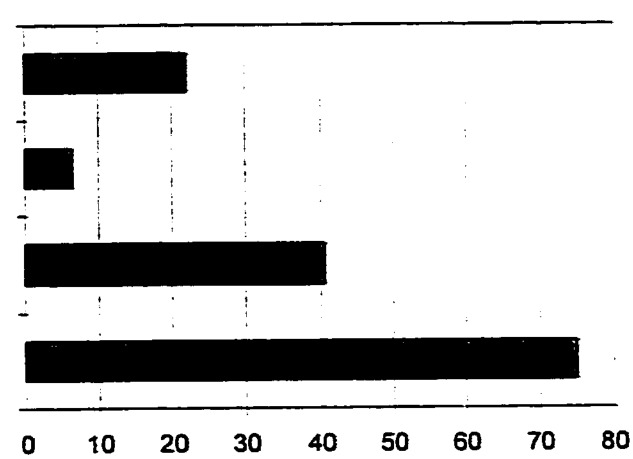


Figure 3.9: Filters Generally Used

About 41 percent of designers specify high efficiency particulate air filters (HEPA), 6 percent recommend electrostatic air cleaners (EAC), and 22 percent of them specify other types of filters. It is important for the HVAC designers, who make the filter selection, to know the types of contaminant that are or could be present in the building environment. Air filtration in commercial buildings should consist of media capable of providing 65, 85 or 95% ASHRAE dust spot efficiencies, depending upon anticipated indoor air contaminant concentration, outdoor air particulate concentration and the percentage of outside air being used. The air filtration efficiency normally specified by designers is shown in Figure 3.10. About 50 percent of the designers specify 70-80% efficiency, where as 31 percent recommend filtration efficiency of more than 90%. Approximately 13 percent of them design for 60-70% filtration efficiency while some 16 percent use other percentages of air filtration efficiency.

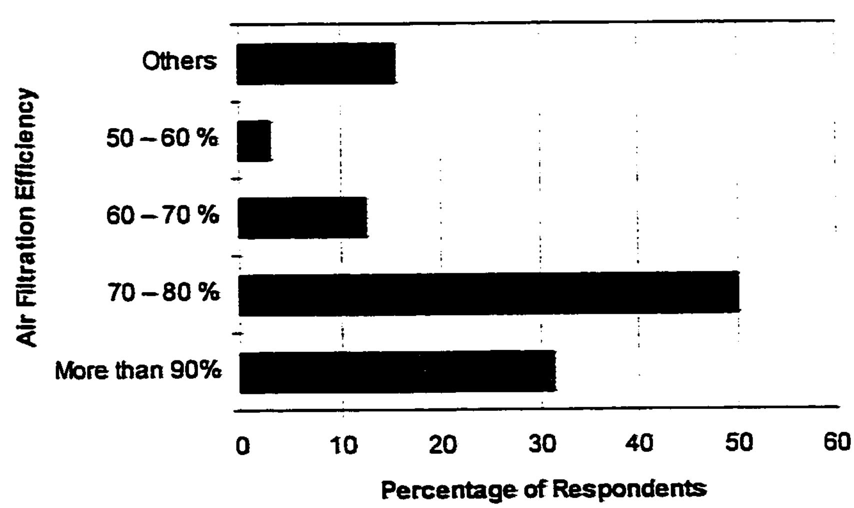


Figure 3.10: Specified Air Filtration Efficiency

High efficiency filters are helpful in providing cleaner air and cleaner HVAC system coils, duct works, diffuser, etc. which reduces maintenance cost. The main problem associated with these filters is their higher cost.

3.4.4.2 Maintenance Accessibility

Maintenance accessibility of the HVAC equipment is one of the main issues that all HVAC designers should take into consideration while designing the mechanical systems of buildings. During their interview, most of the surveyed designers have emphasized its importance during the design stage. To provide better control over IAQ, HVAC design must take into account the minimum maintenance requirements, equipment access and serviceability, and overall equipment reliability.

In response to the question regarding the measures they take during the design of coil condensation pan to ensure complete condensate drain and prevent blockage, 81 percent of the designers have indicated positively and only about 19 percent responded negatively. Water accumulation or leakage around the cooling coils results in microbial growth. Proper condensate drain system, including the piping connection should be ensured during the design stage. The drainage system should be trapped, and the proper slope from the condensate pan to the drain location should be made.

3.4.4.3 Ductworks

The ductwork system is one of the most important components of the HVAC system affecting the air quality. It becomes pathway for pollutants and transports it from one place to areas throughout the building.

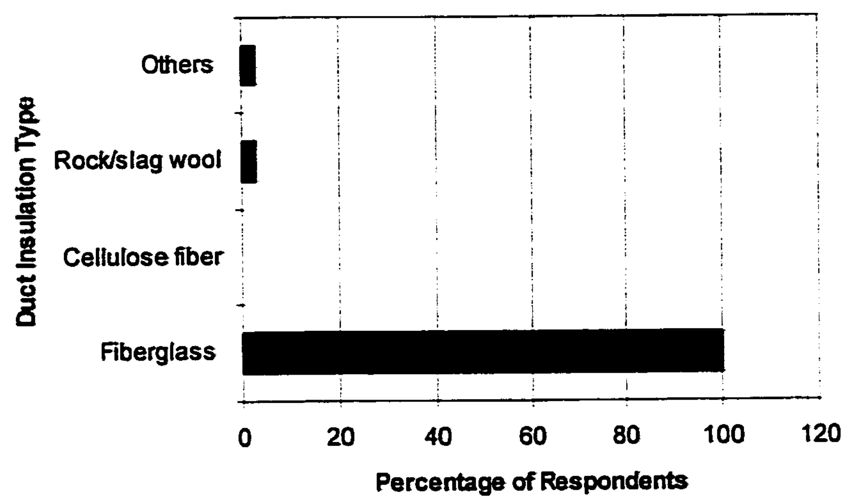


Figure 3.11: Types of Thermal Insulation used in HVAC Systems

A well-designed and well-installed ductwork and air distribution system is detrimental to proper indoor air quality. Regarding the duct insulation, fiberglass is too popular with the designers. All the surveyed designers specify it as shown in Figure 3.11.

Regarding the location of insulation with respect to the duct, all designers specify external insulation. Their main concern with the internal insulation is its characteristic to support biological and mold growth when subjected to humid air. Also the contaminants that were not removed by the air filtration system and condensate drain pan can be easily trapped by the internal lining, thereby promoting microbial growth.

3.4.4.4 Local Exhaust

About 53 percent of the designers allocate separate areas for smoking with local exhaust whereas 47 percent do not allocate as shown in Figure 3.12.

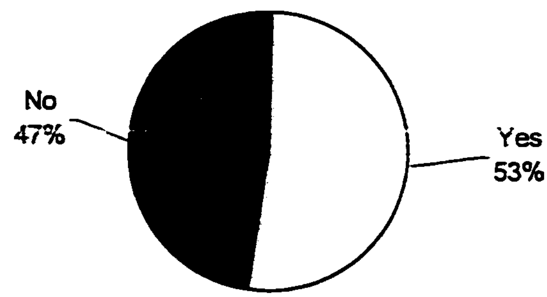


Figure 3.12: Percentage of Designers Allocating Separate Smoking Areas

Separate exhaust system in smoking areas is highly recommended. ASHRAE 62-1989 recommends a ventilation rate of 60 cfm (28 L/s) per person for smoking lounges. Negative pressurization of these areas in relation to adjacent areas prevents the migration of contaminated air. Tobacco smoke particles are hazardous as they are inhalable and remain airborne for hours after smoking stops. Passive smoking increases the risk of lung cancer in adults and respiratory illness in children.

All the designers provide local exhaust for spaces with localized contaminant generation. They state that these areas include spaces like toilets, kitchen, chemical labs, photographic shops, etc. During personal interview many affirmed that it is unimaginable to design HVAC systems for such spaces without proper exhaust systems. If local exhaust to these areas is ignored, they have the potential for creating poor IAQ. Particularly for toilets, the exhaust system should be continuously operating during the building's occupied hours. and provision of makeup air to the toilet be made.

3.4.4.5 Outdoor Air Intake

Intake of contaminated outdoor air is a potential cause of air quality problems. It should be designed and located in such a manner that avoids the polluted air to enter the building. Bird screens and mesh be provided on all fresh air intake openings to protect the HVAC system from debris. Other factors, too. have an impact on IAQ such as the prevailing wind direction that could introduce pollutants from a distance to the outdoor air intake. In response to the question related to the fresh air intake considerations, almost 84 percent of the designers agree that location of air intake is their primary consideration as can be seen in Figure 3.13. About 66 percent of the designers take into consideration the bird screens and mesh at the exterior opening of fresh air intake.

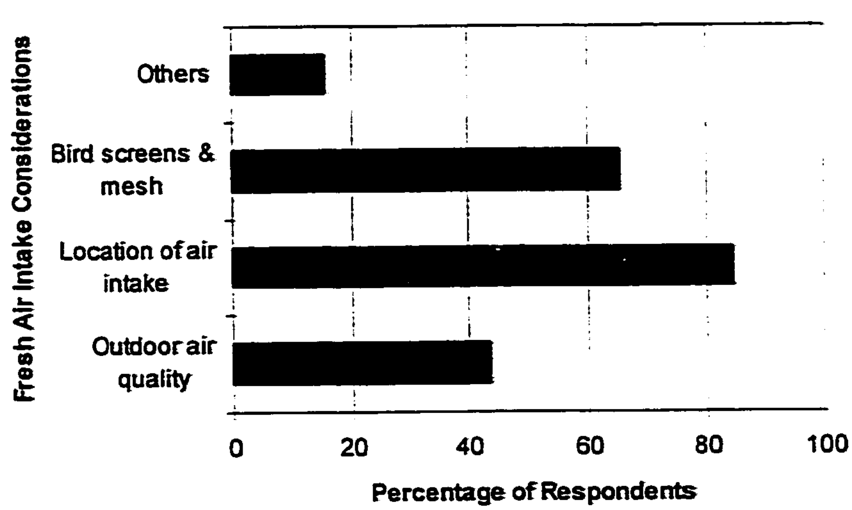


Figure 3.13: Fresh Air Intake Design Considerations

The quality of outdoor air, which is being taken inside the building as fresh air, is a cause of concern to about 44 percent of the designers. About 16 percent of the designers have other than these concerns such as the height from where the fresh air is taken in, wind direction, location of building etc.

3.4.4.6 Air Distribution

The airflow patterns and currents that are created from the locations of supply diffusers and return grilles affect the perception of comfort in spaces. These currents also cause local cooling of portions of the body. Regarding the consideration of the air distribution pattern in spaces when selecting and locating the supply and return air grilles, all designers acknowledged this practice. The layout of air distribution grilles and diffusers play an important role in proper air mixing and temperature control within a space. All of them have expressed that the air distribution pattern holds the key to proper design of any building.

3.5 Summary

Responses to various questions of the questionnaire have been shown graphically and explained in detail in the previous section. This section involves the discussion of results of HVAC designer's questionnaire survey.

Since 84 percent of the designers have more than five years of design experience and about 53 percent have more than ten years of experience, it can be claimed that their responses represent the general HVAC design practice in the Eastern Province of Saudi Arabia.

The most commonly used HVAC systems for commercial and office buildings in this part of the Kingdom are the packaged rooftop units, split systems and the constant volume all-air systems. The designers have suggested that packaged rooftop units are their first choice for two storied buildings. For these types of systems, not the size of building, but the height of the building is the selection criteria. As the height increases, the duct length increases and hence, the heat and pressure loss increases. For medium (3-7 floors) and high rise (8 or more floors) buildings, the designers prefer either the split systems or the constant volume all-air systems. Their preference for medium rise buildings is the split system and for high rise buildings it is the constant volume all-air systems. The disadvantage of split systems in high rise buildings is that in case of refrigerant leakage, it is difficult to detect the exact point.

The most common design considerations that influence the selection of the HVAC systems are the thermal comfort conditions and indoor air quality in any building. 81 percent of HVAC designers have indicated that temperature control of the space is their primary concern. It is encouraging to know that about 75 percent of the designer's equipment selection criteria are also based on indoor air quality issues. However, the remaining 25 percent do not consider the issue of indoor air quality in their equipment selection criteria, which is alarming for healthier indoor spaces. Energy conservation is considered by about 59 percent of the designers for designing and selecting the HVAC systems.

The ventilation rate for commercial and office buildings as specified by ASHRAE is 7-10 L/s (15-20 cfm) per person (ASHRAE standard 62-1989). But it was observed that only about 50 percent of designers abide by the Standard requirements. 34 percent of designers specify ventilation rate between 5-7 L/s (10 to 15 cfm) per person and 16 percent specify between 2-5 L/s (5 to 10 cfm) per person. This is not a healthy design practice in view of the Standard 62-1989.

Almost all designers take some or the other consideration into account while designing the fresh air intake. The location of air intake is the most common concern for about 84 percent of the surveyed designers. About 66 percent of them do consider for bird screens and mesh also, but outdoor air quality is a cause of concern to only about 44 percent of designers. Outdoor air quality becomes especially important in industrial areas and high traffic areas because of their vehicular emissions.

More than 81 percent of designers normally specify air filtration efficiency of greater than 70%. 31 percent of them specify even a higher filtration efficiency of more than 90%. About 13 percent specify 60 to 70%. Hence overall practice in this regard is reasonable. The most common filters used are the media filters, which are recommended by about 75 percent of the designers.

All the designers use fiberglass insulation for the ducting system that is wrapped external to the duct. Use of insulation internal to the duct reduces the noise level but causes degradation and microbial growth after some usage. Some of them have also expressed the fear that using internal insulation could be carcinogenic. However, few of them still use it at the mouth of the air-handling unit for a distance up to two meters. The air distribution patterns in spaces is designed adequately by properly locating the supply and return air grilles, thus providing uniform air circulation.

CHAPTER 4

ASSESSMENT OF IAQ STATUS: OCCUPANTS QUESTIONNAIRE SURVEY

4.1 Introduction

In assessing IAQ in buildings, some investigators have recommended extensive occupant's questionnaire surveys, some others have suggested formal medical examination, while others have focused entirely upon the objective air quality data and the physical characteristics of the building (Collett, et al. 1993). Most of the investigators currently engaged in IAQ testing in commercial buildings have developed complementary ways of eliciting feedback from building occupants. Questionnaire administered to occupants range widely in their degree of detail. They focus on lists of symptoms of discomfort or ill health, perceived attributes of the individual's work environment, such as temperature, humidity, odor, etc., and other data like duration of stay in the building, type of equipment, etc. (Vischer, 1993).

In the Eastern Province of Saudi Arabia, a total of 40 commercial and office buildings were selected for the study. However, the study was conducted in 24 buildings based on the type of HVAC system employed (packaged, split, and all water systems), the ease of accessibility and the size of the building. A total of 504 questionnaires were distributed to the occupants of these buildings.

4.2 Questionnaire Structure

A questionnaire for building occupants (see Appendix C) was developed and administered. This questionnaire was administered with the aim of acquiring information on the following aspects:

(i) to seek general information like age, occupation, duration of stay in the building, and period of occupation of that particular space

(ii) the symptoms they might have observed over a period of time such as headache, irritation, fatigue, skin rash or drowsiness

(iii) their medical history and the behavior of these symptoms

(iv) their perception of work place environment such as temperature, relative humidity, noise and lighting levels, air movement, odor, etc.

Hence, the questionnaire was divided into different sections including general information, symptoms, and work place environment. The results from this questionnaire survey have been used to quantify the prevalence and type of health and comfort complaints.

4.3 Conducting the Survey

4.3.1 Briefing

The occupants of the selected buildings were introduced to the objectives of the study and its importance for the work environment. Their concerns were personally responded to and they were ensured that their identity will not be exposed. The researcher explained the academic nature of the research and that the data will be used solely for the stated purpose. Apart from this, it was communicated to them that the study would come up with recommendations to improve their working environment, and were encouraged to participate in the study by filling in the questionnaires that were available in English and Arabic.

4.3.2 Response to Survey

Most of the occupants appreciated the objectives of the study and came forward to provide their feedback by filling in the questionnaire. The researcher preferred to get them filled in his presence so that if the occupants have any concern it can be clarified instantly. However, in some buildings the questionnaires were collected the following day or the day after because of the busy schedule of occupants.

4.4 Questionnaire Analysis

The analysis of the occupant's questionnaires is discussed in this section. The questionnaire, as illustrated in Appendix C, has been divided into three sections namely, general introduction of occupants, symptoms experienced in the building, and the workplace environment. The office buildings have been classified as old and new buildings based on the year of construction. In the year 1989, ASHRAE reviewed its standards, and hence the buildings constructed before 1989 have been termed old. However, commercial buildings have not been classified as old and new because of their meager number in the Eastern Province. Most of these buildings are newly constructed in the 1990's.

4.4.1 General Information

The occupants of these buildings were asked to provide general information about themselves and the working space. They were asked questions like their age, occupation or profession, their duration of stay per day in that particular space under investigation, and the period of occupation of that space.

The temperature, relative humidity, air velocity, metabolism rate. and clothing insulation are the primary factors that directly effect the thermal comfort. However, there are several secondary factors, like age and sex. which influence the perception of comfort. Since the metabolism rate decreases with age, the ambient temperature level for the homes of older people is often higher than that for the younger people (ASHRAE Handbook. 1997). Almost 43 percent of the surveyed occupants in the investigated buildings were in the age group of 20 to 30 years, and about 38 percent were in the age group of 31 to 40 years. Only 0.4 percent crossed the age of 60 years.

The surveyed occupants were asked to indicate the time duration they spend in those spaces. The longer they stay, the more reliable is their response as they can comment on what they have experienced in that space. About 65 percent of the surveyed occupants spend more that eight hours in their working environments, and about 29 percent spend between 6 to 8 hours. None spend less that 4 hours, with only a few (about 5 percent) spending about 4 to 6 hours. This information gives credibility to the collected data as these occupants spend a reasonable amount of time inside the spaces under investigation. The surveyed occupants were either office workers or were working in commercial buildings. The offices usually work for about eight to nine hours. The commercial establishments operate for about eight to ten hours in two shifts, that is morning and evening. 69 percent of the surveyed occupants suggested that they were working in those environments for more than a year. Another 19 percent indicated of occupying those spaces between 6 months to one year. And only 6 percent had occupied for less than 3 months. Again this data increases the reliability of responses of the occupants as a majority of them have been working in their environments for more than one year.

4.4.2 Symptoms

In this section of the questionnaire, the occupants of the investigated buildings have been asked to comment on the type of symptoms they have observed during their stay inside those buildings. They were asked to provide information as to how frequently these symptoms occur while working in their environments, do they disappear upon leaving the building, do they occur during a particular time of the year, how long do they last, do they suffer from any medical problem related to these symptoms, and their perception of working environment. The objective of this part of questionnaire is to get feedback from the occupants regarding their health complaints and relate them to IAQ status in the building.

It has been widely reported in literature that the occupants suffer in sick buildings. These include eye irritation, headache, throat irritation, fatigue, chest burning, throat irritation, nose irritation, dry mouth, drowsiness, and skin related problems. A number of factors may be responsible for these health effects including insufficient ventilation, poor air distribution, presence of organic dust molecules of biological origin, and other physical, chemical, biological, and psychological factors.

The symptoms experienced by surveyed occupants in old office, new office, and commercial buildings are shown in Figure 4.1.

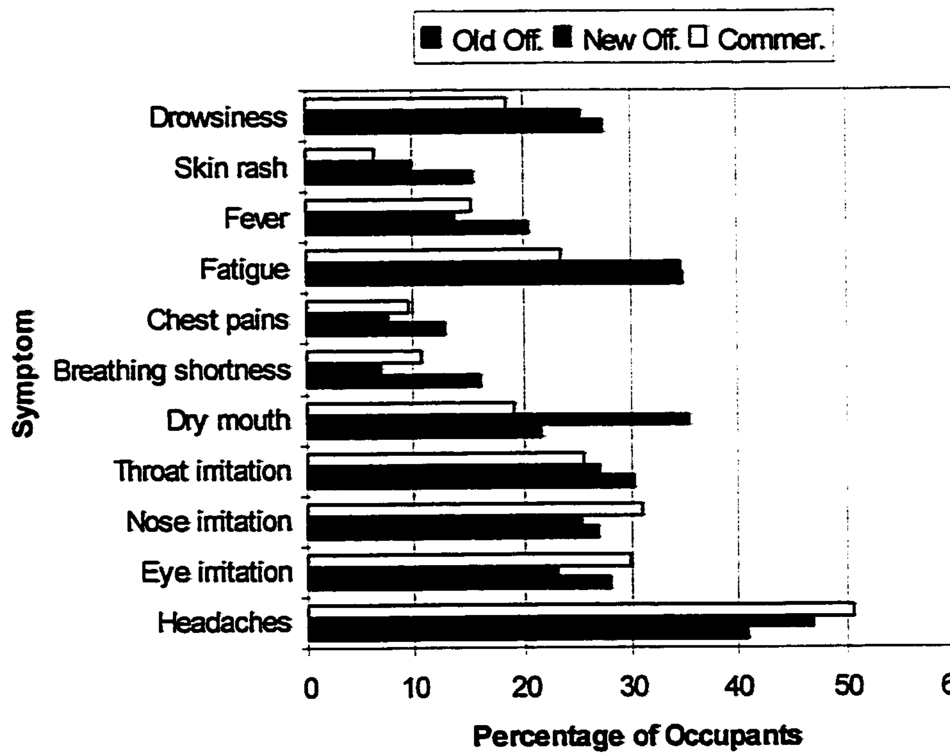


Figure 4.1: Symptoms Experienced by Occupants

Headache is the most common and prominent complaint in all the three types of buildings. As can be seen in Figure 4.1, between 40 to 51 percent of the surveyed occupants have complained about this problem. This may be due to the presence of airborne pathogen, improper temperature, inadequate light, glare, or noise. The highest percentage of complaints has been received in commercial buildings, which could be related to glare and noise.

Fatigue is the next common complaint that has been reported by about 31 percent of total surveyed occupants in all the three types of buildings. The occupants of the old and new office buildings have registered the maximum percentage of complaints. The causes of fatigue could be due to the presence of microbial aerosols, excessive concentration of volatile chemicals. poor labor relations, uncomfortable seating, repetitive motion, or overcrowding. Since a majority of the problems have been reported in old and news office buildings. it could be sensible to relate it to uncomfortable seating conditions. repetitive motion, and overcrowding. The presence of microbial aerosols and other pollutants cannot be ruled out in old office buildings.

Approximately 23 to 30 percent of the surveyed occupants have complained about the eye, nose and throat irritations in all the three types of buildings. This indicates that the rate of dissatisfaction or the complaints related to eyes, nose and throat are similar in all these buildings as shown in Figure 4.1. The probable reasons for these irritations may be the excessive concentrations of volatile chemicals such as solvents and formaldehyde. Some people are more sensitive to these irritations, which may be accompanied by other symptoms such as headache, nausea, or fatigue. Eye irritation may be due to the problems associated with lighting such as insufficient light, glare or flicker. Other reasons could be related to the ergonomic problems like uncomfortable seating postures.

Dry air or the presence of airborne pathogens in the space or the inadequate controls of source emissions or contamination causes nose and throat irritation.

Drowsiness has been reported by about 24 percent of the total surveyed occupants in commercial and office buildings. The highest percentage of about 27 percent has been reported in old office buildings, followed by about 25 percent in new office buildings. Only 18 percent of surveyed occupants have complained about drowsiness or weariness in commercial buildings. Drowsiness could due to asphyxiant or poor temperature control or the levels of light/noise.

Almost 24 percent of the total surveyed occupants have complained about the dryness of mouth inside these buildings. As can be seen in Figure 4.1. 17 percent of the occupants have reported to experience fever while occupying these spaces. The reasons could be improper control of temperature and humidity, poor distribution of air, absence of humidifiers, etc.

The surveyed occupants were asked to comment whether these symptoms disappear after they leave the space. Around 45 percent have indicated that these symptoms do disappear once they leave their buildings. However, about 23 percent have complained that they are not relieved even after vacating the space.

The frequency of occurrence of these symptoms indicates the seriousness of the existing problem. Hence, the occupants were inquired as to how often these symptoms occur. Their response is shown in Figure 4.2.

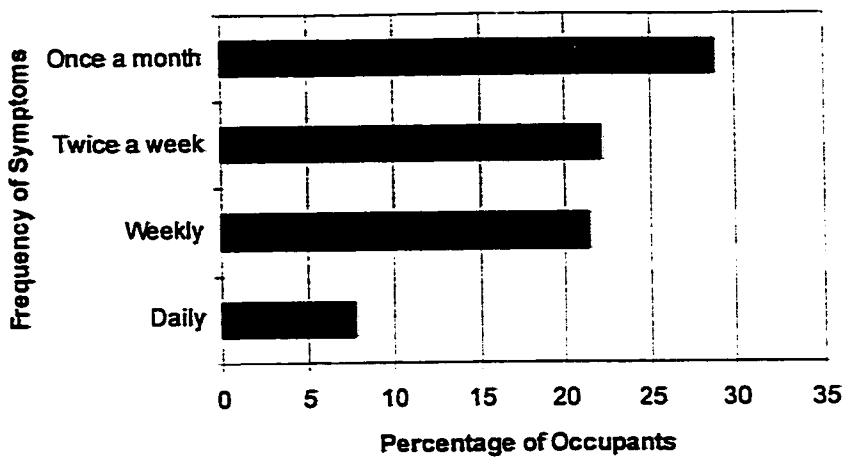


Figure 4.2: Frequency of Symptom's Occurrence

Only about 8 percent of the surveyed occupants have complained that they suffer from these symptoms daily. Almost 22 percent have reported to observe these symptoms weekly once, another 21 percent suffer approximately twice a week, and 29 percent have observed it once a month. For a building to be categorized as "sick building", at least 20 percent of the building occupants display symptoms of illness for more than two weeks, and the source of these illness could not be positively identified. Since only 8 percent of the surveyed occupants have shown dissatisfaction with their environment, the buildings cannot be called as sick. The symptoms that have been reported once a week or twice a week could be due to a number of reasons, like work stress, restlessness, improper working conditions, etc. Other rare symptoms could be due to changes in weather and environmental conditions, since about 39 percent of surveyed occupants have reported to suffer from these symptoms in summer as against only 20 percent in winter.

The occupants were asked to provide information regarding their health condition. The medical history of the surveyed occupants is shown in Figure 4.3.

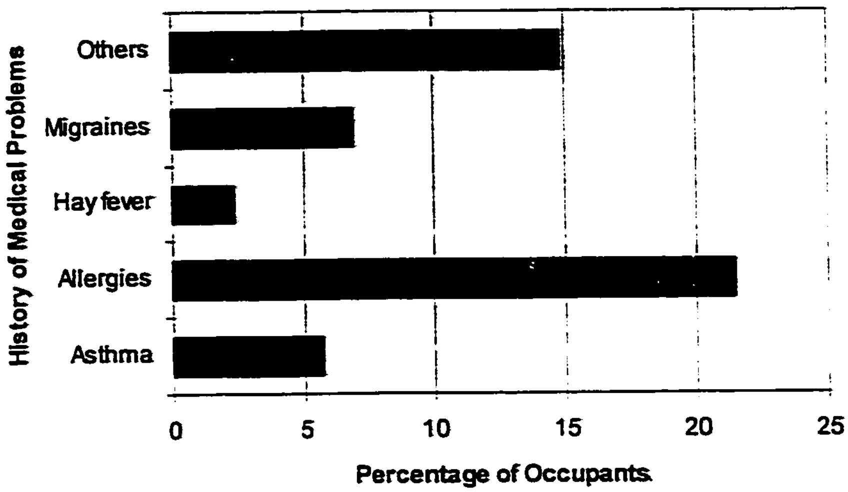


Figure 4.3: History of Surveyed Occupants Suffering with Various Medical Problems

It is important to know the medical history of the surveyed occupants, so as to relate the observed symptoms to their problems. As shown in Figure 4.3, about 7 percent of the surveyed occupants suffer from migraines, 6 percent from asthma, and about 21 percent from different allergies. These problems could have a direct impact on the response of occupants who have complained of various symptoms while working in their environments. For example, the occupants suffering from migraines have reported to suffer from headache, which could be due to disease rather than poor working conditions.

In spite of all these symptoms, almost 85 percent of the surveyed occupants have preferred to call their working environment as comfortable and only 14 percent of them have termed it as uncomfortable. Less than one percent feels it as unbearable. The percentage of occupants who feel comfortable is higher in new office buildings, which are about 97 percent, due to better acoustical condition of HVAC system, proper lighting, and neat surface finishes, etc. The percentage of discomfort in old office and commercial buildings is little higher because of many reasons including the presence of large fenestration, smoking inside spaces, poor HVAC maintenance, etc. 51 percent feel better when they leave that space as against about 47 percent who do not feel any difference. This could have a psychological reasoning as people feel relax and free from stress after the day's work, or could feel more comfortable with the outside fresh air except for few days of hot and humid season.

4.4.3 Work Place Environment

The occupants of these office and commercial buildings were asked to identify the levels of comfort or discomfort with regards to the environmental parameters. These parameters include the temperature, relative humidity, noise level, lighting level, and the air movement inside these spaces. These are the indicators of the goodness of any environment and helps in assessing the general conditions of the building. In this section of the questionnaire, the occupants were asked to comment on the environmental parameters, complaints regarding the HVAC systems, presence of odor, tobacco smoking policy and dust collection.

4.4.3.1 Temperature

As mentioned earlier also, temperature is perhaps the most important environmental factor that determines the perception of comfort. Generally humans are sharp to react to this parameter. The response of the surveyed occupants with regard to thermal perception is shown in Figure 4.4.

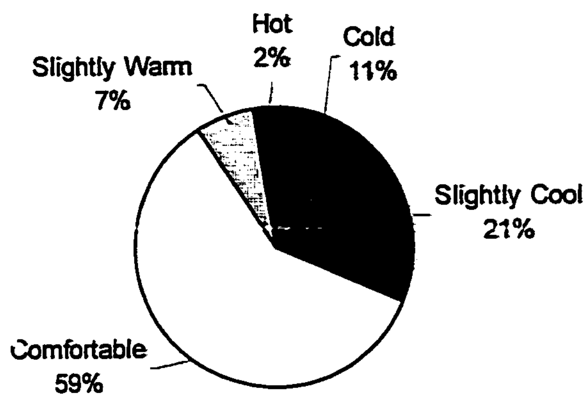


Figure 4.4: Temperature Perception

A total of 59 percent of the surveyed occupants in commercial and office buildings perceive the environment as thermally comfortable. About 21 percent apprehend it as slightly cool and only about 7 percent sense it as slightly warm. In other words only 13 percent of the total surveyed occupants are thermally uncomfortable with the environment that either feel cold or hot. Occupants of the new office buildings have shown the highest percentage of thermal satisfaction with their environment. Almost 79 percent of the occupants in these buildings perceive the temperature as comfortable, and only about 8 percent have shown dissatisfaction. This may be due to the excellent working condition of the air-conditioning units or a proper maintenance policy. In contrast to these buildings, the old office-building occupants are least satisfied with about 22 percent showing dissatisfaction. The reasons for this could be poor maintenance and operating conditions of the HVAC systems, infiltration and exfiltration, problem in control system, improper placement of thermostats, etc.

4.4.3.2 Relative Humidity

The second most important environmental parameter that governs the perception of comfort in humans is the relative humidity, that is the percentage of moisture in the air relative to the amount it could hold if saturated at the same temperature. Humidity affects how the occupants subjectively feel. The perception of relative humidity by the respondents is illustrated in Figure 4.5. About 72 percent of the surveyed occupants have suggested that they feel comfortable with the humidity levels inside the spaces, where as only 1 percent have complained about severe humidity inside the building. 12 percent of the respondents have commented about the working environment as little humid and about 15 percent complained about dryness.

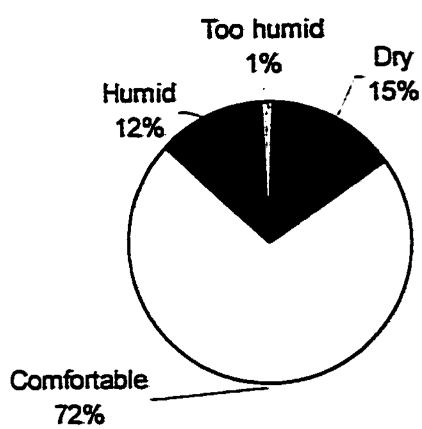


Figure 4.5: Relative Humidity Perception

Increasing the amount of outside humid air in summer, to flush indoor air contaminants, can increase indoor humidity levels. This leads to an increase in microbial growth and damage to surface finishes. The effect of increased ventilation on humidity control is of concern in hot and humid climates. Occupants become more susceptible to adverse health conditions, such as allergies, depending upon the exposure to humidity levels. Low humidity levels, especially in winter, is responsible for dehydrated mucous membranes, sinus irritation, headaches, etc.

In the case of relative humidity also, about 82 percent of respondents in new office buildings have shown their satisfaction with the environment, which is the highest percentage in all the three types of buildings. The least comfortable are the occupants of the old office buildings, where only about 62 percent have shown their satisfaction. 16 percent of the occupants have complained about the presence of humidity in these buildings. One of the reasons could be the intake of outside humid air as indicated earlier to dilute the indoor generated contaminants.

4.4.3.3 Noise Level

The acoustical level also affects the perception of comfort. Sound and vibration are created by a source, then transmitted along one or more paths, and reach a receiver. Noise could be defined as any unwanted sound and does not have to be loud. Loud noise can cause hearing loss and could affect stress level and the heart rate. The noise level as perceived by the respondents in the investigated commercial and office buildings is shown in Figure 4.6.

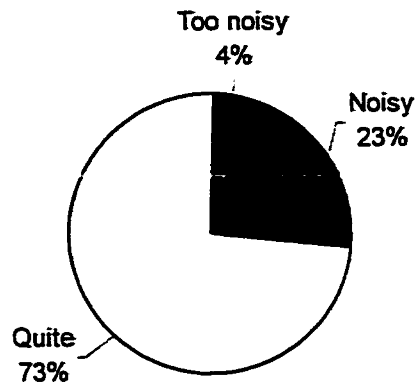


Figure 4.6: Noise Level Perception

Around 73 percent of the surveyed occupants have revealed that they are acoustically comfortable in their environments. However about 23 percent have suggested the conditions are noisy with about 4 percent claiming it to be too noisy. ASHRAE suggests NC=35 to 40 for Offices. HVAC systems are a major source of noise inside buildings as they create and transmit sound via ducts. The response to sound is not only physiological, but also psychological and depends on the state of attitude of the listener, which can vary. Hence, the effect of noise is often unpredictable (ASHRAE, 1997).

In terms of noise level also, the new office buildings are reportedly performing well as about 88 percent of respondents in these buildings have shown satisfaction with the noise level. Where as 28 percent of respondents in old office buildings and about 25 percent in commercial buildings have categorized the space as noisy. In old office buildings, the reason could be the improper maintenance of HVAC system. In case of commercial buildings, the noise could be due to the presence of crowd, inadequate functioning of the air-conditioning unit, etc. Sound sources in HVAC systems are numerous, such as the reciprocating and rotating equipment (like fans, motors, pumps), air and fluid noises (flowing through ductwork, piping systems, grilles, diffusers), excitation of surfaces (friction, movement of mechanical linkages), etc.

4.4.3.4 Lighting Level

Another important parameter that decides the perception of comfort in humans is the lighting levels in their work environment. Both, high lighting levels or glare and low levels or dim light are harmful to human eye. The response of surveyed occupants in commercial and office buildings is illustrated in Figure 4.7.

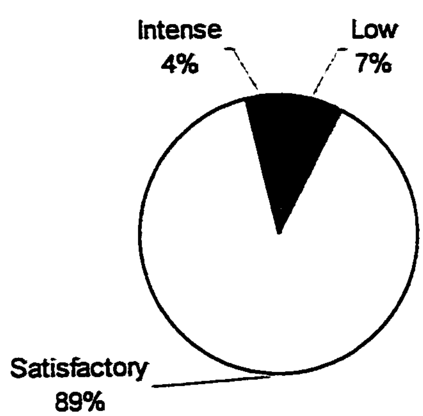


Figure 4.7: Lighting Level Perception

As shown in Figure 4.7, about 89 percent of the respondents are satisfied with the lighting levels in their workplace environment. However, about 7 percent have complained about low lighting levels and 4 percent have asserted about high lighting levels. The complaints regarding the dim lighting levels have been reported by the respondents in old office buildings where the reasons could be the poor lighting maintenance, rough interior surface finishes, and improper design. The occupants of the commercial buildings have recorded the complaints regarding intense lighting. The reason for this could be the high intensity lights that are installed in commercial buildings to attract customers. Since lighting is a major space thermal load component, an increase in the intensity of lighting is directly proportional to increase in thermal load. Both the high intensity and dim light cause strain on the eyes and sometimes cause irritation and headaches.

4.4.3.5 Air Movement

The air movement within the space from supply to return or exhaust should be moderate with relatively uniform air velocity to ensure proper distribution of air in all parts of the buildings. It should be directed towards and across the sources of heat generation. The occupants of the investigated buildings were asked to comment regarding their perception of air movement in their spaces. Their responses are shown in Figure 4.8.

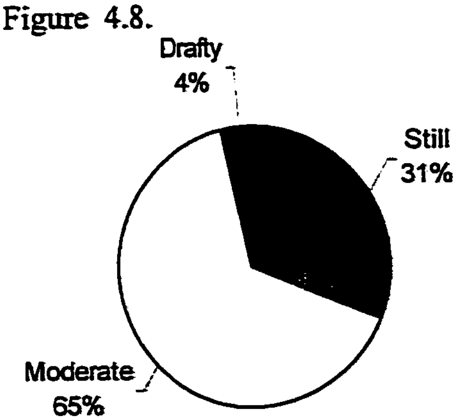


Figure 4.8: Air Movement Perception

A majority of the occupants are satisfied with the air movement in the investigated buildings. About 65 percent of the surveyed occupants feel that the air movement is moderate, and almost 31 percent perceive it as still. Only about 4 percent of respondents have complained about draft, which is an undesired local cooling of the human body caused by air movement. Draft is an annoying factor that causes severe discomfort with the environment. It has been observed that the thermal acceptability is unaffected in neutral environments by air speeds of 0.25 m/sec or less (ASHRAE, 1997). The reasons for draft could be related to the poor design and/or operation, and maintenance of HVAC systems. It also depends upon the layout of supply diffusers and return grilles.

4.4.3.6 HVAC Systems

The HVAC systems and their performance decide the goodness of air quality inside buildings. As discussed earlier, these systems can affect IAQ in two ways, that is, they could be the source of contamination due to dirt and moisture buildup caused by improper maintenance or equipment age, or could be the pathway through which the contaminants enter the space. The occupants of commercial and office buildings were asked to provide information regarding the duration of usage of these systems per year, their concerns and complaints for the installed systems, and the frequency of maintenance of these units.

About 73 percent of the respondents have indicated that the HVAC systems are operational for the whole year (year-round air-conditioning). Another 21 percent of the surveyed occupants have reported that these systems are employed for about nine months per year. Since the climatic condition in the Eastern Province of Saudi Arabia is generally hot and humid for at least six to eight months, and the remaining period is usually comfortable, some of these buildings attempt to conserve energy by keeping their systems off for this season. Some of the occupants were ignorant regarding the number of months for which the HVAC system is operational, and the frequency of its maintenance.

The surveyed occupants were requested to identify the specific complaints pertaining to the air-conditioning systems. Figure 4.9 illustrates the occupant's complaints for their HVAC systems in the three types of investigated buildings.

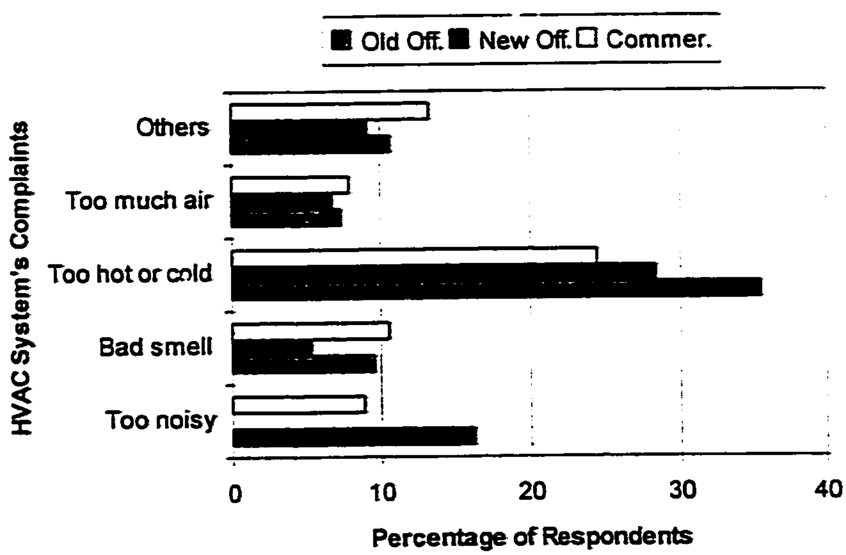


Figure 4.9: Complaints about HVAC Systems

When asked about complaints regarding their HVAC systems, a high percentage of occupants reported that their systems are either excessive hot or cold as shown in Figure 4.9. The occupants of the old office buildings have the highest percentage of dissatisfaction related to this complaint, which are about 35 percent. It could be due to the building being over-crowded, or due to presence of large glass area as envelop to the building or due to poor maintenance practices. The complaint in commercial and new office buildings could be due to the condition of air-conditioning equipment and inadequate operational practices. It was observed in new office buildings, as can be seen in Figure 4.9, that there is no sound pollution, and the occupants are acoustically comfortable.

Another complaint that is evident in old offices is the noise coming out of the HVAC equipment as can be seen in Figure 4.6. This could be due to the equipment age, lose fittings, and improper maintenance of these units. Other problems like bad smell and too much air are well within 10 percent in all these buildings. Bad smell could be attributed to the perception of humid space by about 12 percent of the respondents as shown in Figure 4.5. The importance of HVAC systems could be understood with the fact that these systems are responsible for about 60 percent of the building generated IAQ problems and has the potential to resolve up to 80 percent of the problems (Hansen, 1991). Many IAQ investigators have suggested that a few corrective strategies for these systems would improve the existing conditions.

Proper HVAC system's maintenance is decisive to better IAQ. The lack of trained maintenance personnel or an unsound maintenance policy is detrimental to the HVAC system's performance and can increase the risk of creating sources of contamination within these systems. Dirty blocked screens of air handlers, malfunctioning humidifiers, dirty filters, high pressure drops, blocked ducts, dirty diffusers, etc. are all indications of poor maintenance program. Almost 42 percent of the surveyed occupants have indicated that the maintenance of these systems is carried out annually, and about 28 percent have reported twice a year. Around 9 percent of the occupants have indicated that it is conducted once in every 9 months. Maintenance conducted with these frequencies is reasonable and practical, however it is better to carry it out every six months. There are about 6 percent of the occupants who have indicated that the maintenance of these systems in their buildings is carried out once in two years. This illustrates a poor maintenance policy in those buildings, which could be responsible for the reported symptoms and dissatisfaction with the environmental parameters.

4.4.3.7 Odor

The presence of odor in any space is an indicator of IAQ problem. The odor could be due to cigarette smoking, car exhaust, sewage gas, furniture, musty smell, and body odors. The common complaints due to the presence of odor include headaches, dizziness, tiredness, respiratory problems, skin irritation, coughing, sneezing, and eye, nose, & throat irritation.

The response of surveyed occupants regarding their perception of odor is shown in Figure 4.10. A total of about 40 percent of surveyed occupants in all the three types of buildings do not observe any abnormal odor in their spaces. It shows their satisfaction in terms of odor.

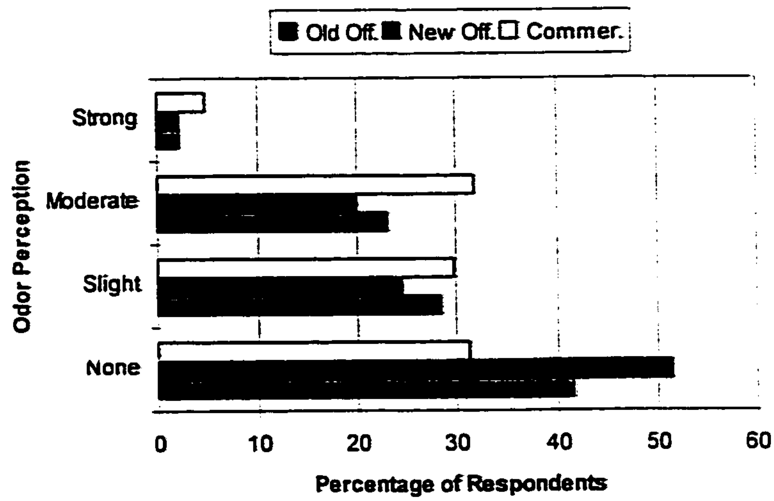


Figure 4.10: Odor Perception

As can be seen in Figure 4.10, the occupants of new office buildings are the most satisfied with about 52 percent showing satisfaction with the odor level in their workspaces. However, 31 percent of occupants in the commercial buildings are the least numbers who are satisfied with their environment. Intensity is a quantitative aspect of a descriptive analysis, stating the degree to which a characteristic odor is present. About 28 percent of the total surveyed occupants have reported slight presence of odor, and almost 26 percent of occupants have commented on the moderate scale of odor presence. Very few occupants, about 3 percent, have reported the presence of strong odor in those buildings. It has to be noted, however, that all persons exposed to a given odor are not likely to agree whether the odor is acceptable or unacceptable. It rather depends on a complex combination of associations and is not a characteristic of odor itself (ASHRAE, 1997).

The occupants were also asked to identify the possible causes for the presence of odor in their surroundings. 36 percent of the total surveyed occupants have linked the presence of odor to the cigarette smoking in their work areas. This is a serious problem as the smoke is circulated and re-circulated in all parts of the building via the HVAC systems. Around 16 percent of the occupants have indicated that the odor is because of the close proximity to toilets. This is serious in spaces where there are either non-existent or insufficient exhaust fans in toilets, which compels the air from toilets to mix with the return air and thus circulates into the whole building. Others have associated it with car exhaust, carpet, furniture, or other sources like body odor, building materials, etc.

The surveyed occupants were asked whether they are habituated to tobacco smoking. About 40 percent of the total respondents reported themselves to be smokers as against 60 percent non-smokers. This is an alarming figure as the hazards of inhaling mainstream smoke that is inhaled by smokers and sidestream smoke that is produced at the burning end of tobacco products are well documented in literature. Even if a small percentage of smokers smoke inside the conditioned spaces, the particles of tobacco smoke remain airborne for hours after smoking stops. Moreover, the smoke contains over 3800 chemical compounds, many of which are irritants, carcinogens, mutagens, and teratogens (Hays, et. al, 1995). The occupants were also asked to comment on whether smoking in their work environment bothers them. 62 percent of respondents opined that it does irritate them. However about 38 percent are not bothered by others smoking in their vicinity. These are probably the smokers themselves who have no reservation for smoking inside enclosures.

4.5 Summary

This section deals with the summary of results of the occupant's questionnaire in commercial, old and new office buildings. Responses to various questions have been analyzed and discussed in the previous section. A total of 504 questionnaires were distributed to the occupants of 24 buildings in the Eastern Province of Saudi Arabia.

Around 80 percent of the surveyed respondents were young males less than 40 years of age. It is important to mention here about their age and sex as these factors have an influence on the perception of comfort conditions (Collett. 1993). Only men have been distributed the questionnaires as women do not go to work public places in Saudi Arabia, and hence only men occupy the office buildings. Almost 95 percent of the surveyed occupants spend more than 6 hours inside their work environments, which gives credibility to the collected data. They have been explained the objectives of the study and were requested to give their feedback on the given questionnaire.

A standard questionnaire is of great value for evaluating the goodness of buildings in terms of IAQ. Their results may be used to quantify the prevalence and type of health and comfort complaints. Poor IAQ can be implicated in a variety of health related symptoms that includes eye irritation, headaches, coughs, asthma, allergic reactions, lethargy, shortness of breath, nausea, dizziness, etc. The major problem that has been reported by the respondents is the headache with about 46 percent suffering from it. Fatigue is the next major problem with about 31 percent of the respondents reporting it, followed by eye, nose, and throat irritations that have each been reported by about 28 percent respondents. Other noticeable problems include drowsiness, dry mouth, and fever. More or less these symptoms are similar in all the three types of buildings that have been investigated.

About 45 percent of the respondents reported that these symptoms disappear once they leave the work place environment. However 23 percent do not agree with them and indicated that the symptoms continue even after they leave those buildings. The reasons for these conditions include their health conditions, attitude towards work, working conditions, workplace environment, and the weather conditions. Only about 8 percent of the respondents have reported to observe these symptoms daily, 22 percent observe them twice a week, and about 21 percent observe them once a week. These figures clarify the picture that only a small percentage of occupants are dissatisfied most of the time. The frequency of occurrence of these symptoms in commercial buildings is higher than in office buildings. The reasons could be the level of interaction with various people, contaminant generation due to varied activity, and the presence of smoke and dust. Most of the complaints have been reported during summer and evenings, which again implies that these symptoms have a seasonal impact.

These are the moments when the load is at its peak. since the summer is long in this part of the world and people prefer to shop at night.

The occupants were asked to provide their medical history to know if they were suffering from any disease that could have an impact on the outcome of the survey results. About 21 percent suffer from allergies, 7 percent from migraines, and 15 percent from some other health effects. About 6 percent of them were suffering from asthma.

When asked to describe the comfort conditions of their working environment, 85 percent of occupants reported that the space is comfortable. However, 14 percent were uncomfortable with their surroundings. The reasons for dissatisfaction could be the complaints related to HVAC systems and the lack of maintenance in some buildings.

The levels of comfort or discomfort with the environmental parameters were inquired from the occupants. These parameters include the temperature. relative humidity, noise level, lighting level, and air movement. These are the indicators of the general comfort conditions in any building. 87 percent of the total surveyed occupants perceive the environment as thermally comfortable. Slightly cool and warm conditions have been included in this category. Only cold and hot conditions have been considered as thermally uncomfortable. With regard to relative humidity, about 71 percent of respondents perceive it as comfortable and the rest either feels humid or dry in different spaces. Regarding the acoustical performance of buildings, almost 74 percent of surveyed occupants perceive the environment as quite. About 23 percent feel it as moderately noisy and only 4 percent opine it to be too noisy. Almost 89 percent of the occupants are comfortable with the lighting levels in their workspaces. Only about 7 percent complained regarding dim lighting and 4 percent about glare. 90 percent of the occupants perceive the air to be clean, and almost 96 percent feel the movement as either still or moderate. Only about 4 percent of the occupants have complained about the drafty conditions. Hence a majority of the occupants are satisfied with the environmental conditions in their surrounding to a larger extent. A minor percentage of dissatisfaction cannot be ruled out in any space, which depends on a number of factors like their medical history, workloads, and attitude. It is almost impossible to design a space that provides comfort and satisfaction to all the occupants without any room for dissatisfaction.

Information regarding the HVAC systems, its maintenance practices, and health related issues associated with these systems, were sought from the occupants of these buildings. 73 percent of the respondents reported that the systems are operational throughout the year. This may be due to the weather conditions in the Eastern Province, which is usually hot and humid for about 6 to 8 months. About 30 percent of the surveyed occupants have complained that these systems provide either too hot or cold environments. Reasons for this complaint include direct throw of air from the supply diffuser, or position near the return grilles, or poor distribution of air. Almost 79 percent of the occupants have indicated that the maintenance of these systems is carried out at least once a year in their buildings. However, some occupants were found to be ignorant on this issue.

In response to a question regarding the presence of odor in the work environment, about 40 percent of respondents have denied its presence. 28 percent concede that it is present in slight magnitude, where as another 26 percent perceive it as moderate. Only about 3 percent have complained about strong odor presence. New office buildings recorded the best performance with regards to the perception of odor, where about 52 percent of occupants do not perceive any abnormal odor. The possible causes for the presence of odor in all the three types of buildings are cigarette smoking (about 36 percent), toilet or sewage gas (16 percent), car exhaust, carpets, furniture and other reasons like building materials, musty smell, chemicals, etc. The main cause of odor in spaces has been identified as cigarette smoking in all the types of investigated buildings. The intensity of complaint is severe in commercial buildings where about 48 percent of occupants have indicated it to be the main cause of odor.

About 40 percent of occupants are tobacco smokers and are not bothered if others too smoke in the enclosures or their work environments. This problem is much severe in case of commercial buildings that recorded the highest percentage of tobacco smokers inside buildings. Around 51 percent of respondents in these buildings are confirmed smokers. Even if a few among these smokers smoke inside the building, it is sufficient to create harmful contaminants, which take hours to dilute and settle down. 59 percent of the surveyed occupants have also indicated that they need to clean their office furniture for dust accumulation with frequencies of at least once per day. Commercial buildings are the worst effected with the problem of dust accumulation. There could be other reasons besides dust accumulation for the cleaning of furniture, especially in commercial buildings to attract customers.

CHAPTER 5

QUANTITATIVE ASSESSMENT OF IAQ AND HVAC PERFORMANCE: A FIELD SURVEY

5.1 Introduction

The fact-finding exercise consisted of a field survey that includes walkthrough inspection of selected buildings and performance related measurements of environmental parameters. Building information is collected that is helpful in identifying possible pollutant sources. Information is also obtained regarding the condition of HVAC systems, its operation, and maintenance. This is followed by instrument measurement of certain environmental parameters that are indicative of indoor environmental quality status. The objective of these exercises is to obtain a first hand information about the actual existing conditions of IAQ and HVAC performance in the investigated buildings.

The first step of investigation was an initial assessment in which information about the buildings and HVAC systems is gathered by the following means:

(i) interaction with the building owner, owner's representative, manager, operation and maintenance personnel. They were briefed about the purpose of the study and information is gathered regarding the building function, occupant's complaints, equipment operation and maintenance schedules. breakdowns or other incidents.

(ii) review of available engineering and architectural drawings. Existing plans and specifications were reviewed where ever possible to acquaint with the original design regarding the type of HVAC system employed. location and capacity of HVAC equipment, planned use of the space. supply. return, and exhaust air quantities.

(iii) finally, a walkthrough inspection to examine the design configuration and operational condition of the building's HVAC system. Every component of the HVAC system is of interest, either as a source of contamination or as a component that fails to provide the required air-conditioning function.

5.2 Walkthrough Inspection

The intent of the walkthrough inspection is to acquire a good overview of occupant activities and building functions and to look for IAQ problem indicators. An initial walkthrough inspection of the building area provides information about all four of the basic factors influencing IAQ i.e. occupants, HVAC system, pollutant pathway and contaminant sources.

5.2.1 Conducting the Inspection

As stated earlier, a total of 24 buildings were selected for the study. Walkthrough inspection was carried out in all these buildings. A building assessment form was developed for this purpose as shown in Appendix D. This was done with the aim of recording the observations about occupied space characteristic, identification of pollutant sources related to HVAC systems, and the general condition of space. Inspection of space conditions includes the suitability of temperature, humidity, lighting level, noise level, smoke and odor. Cooling coils, ductwork and filters are the potential sources of pollutants in the HVAC systems. Hence, information was obtained regarding their conditions, maintenance schedules, microbial growth, etc. Similarly other general conditions of the space are inspected which include the exhaust system, mechanical room conditions, contaminant generation areas, location of air intakes, parking facilities, etc.

5.2.2 Inspection Analysis

As can be seen in the building assessment form in Appendix D, the form is divided into six sections which include the space conditions, duct work, cooling coil section, filters, fresh air intakes, and the general conditions. As stated earlier, the purpose of walkthrough inspection is to get a better understanding of the extent of the problem and to identify its possible causes.

This section deals with the presentation of results of walkthrough inspection in these investigated buildings. It has been subdivided into sections based on the format of the building assessment form. Figures, pictures and tables have been used for better illustration wherever it was found essential. Table 5.1 shows the result of walkthrough inspection in the investigated buildings. The details for each building type can be seen in Appendix H.

Table 5.1: Walkthrough Inspection in Investigated Buildings

	Percentage of Buildings		Percentage of Buildings		Percentage of Buildings	
Noticeable odor	54	None	46	Moderate	0	Strong
Temperature	8	Cold	88	Comfortable	4	Warm
Humidity	0	Dry	92	Comfortable	8	Humid
Lighting level	4	Low	96	Satisfactory	0	High
Vibration and noise level	46	Low	54	Satisfactory	0	High
Dirt	13	Yes	88	No		
Smoking	83	Yes	17	No		
Noticeable flow of air	4	Yes	96	No		
Dampness	0	Yes	100	No		
Proper layout for air distribution	100	Yes	0	No		
Return air plenum	92	Yes	8	No		
Duct lining	0	Inside	100	Outside		
Microbial growth in ductworks	0	Yes	100	No		
Access doors available	100	Yes	0	No		
Drain pans trapped properly	100	Yes	0	No		
Condensation problem	0	Yes	100	No		
Evidence of water leakage	4	Yes	96	No		
Microbial growth in condensate pans	0	Yes	100	No		
Corrosion problem	4	Yes	96	No		
Inspection access available	100	Yes	0	No		
Filter type	100	Media	0	HEPA		
Condition of filter	38	Excellent	54	Good	8	Bad
Moisture buildup	0	Yes	100	No		
Filter location	100	Before	0	After		
Frequency of cleaning	13	2 months	54	3 months	17	6-12 month
Inspection access available	100	Yes	0	No		
Fresh air intake	92	Yes	8	No		
Bird screen obstructed	0	Yes	96	No		
Parking facility or road nearby	83	Yes	17	No		
Exhaust outlet within 25 feet	21	Yes	79	No		
Central exhaust system	38	Yes	63	No		
Separate smoking areas with exhaust	0	Yes	100	No		
Doors to building close tightly	96	Yes	4	No		
Mechanical room conditions	29	Excellent	50	Good	21	Bad
Controls are operational	100	Yes	0	No		
Maintenance/inspection schedule	67	Yes	33	No		
Contaminant generation areas	88	Yes	13	No		

5.2.2.1 Space Conditions

The condition of basic parameters that effect the comfort of occupants in spaces is recorded as the first step of walkthrough inspection. These parameters include odor, temperature, humidity, lighting level. vibration and noise level. dirt. smoke, noticeable flow of air, and dampness.

No significant odor could be perceived in about 54 percent of the investigated buildings as shown in Table 5.1. However, it was moderately present in about 46 percent of the buildings. These buildings were either commercial buildings or old office buildings. This could be due to the presence of cigarette smokers in the vicinity of buildings. About 36 percent of the surveyed occupants have suggested the same. Another possible reason could be the close proximity of toilets without proper exhaust systems. Apart form these. there could be many reasons for the presence of odor like furniture, body odors. car exhaust, carpet, etc. However there were no indications of the presence of strong odor in any of the investigated buildings.

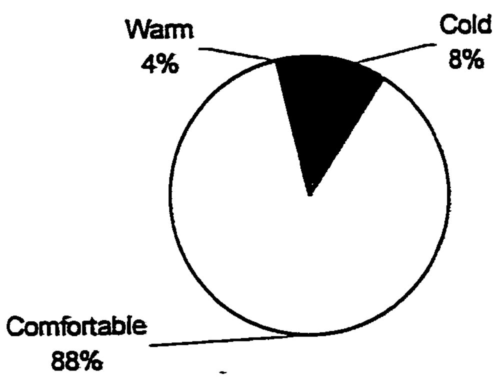


Figure 5.1: Temperature Inspection

The temperature is observed to be comfortable in about 88 percent of the inspected buildings as shown in Figure 5.1. However, 8 percent are perceived as cold and only 4 percent as warm. This is an indication that most of the buildings are performing well in terms of thermal comfort. Only about 13 percent of the surveyed occupants have registered their dissatisfaction with their thermal environment.

The rate of satisfaction is higher in new office buildings among the surveyed occupants as well as the walkthrough inspection. This could be attributed to the new air-conditioning units and adequate maintenance policy. The little dissatisfaction could probably due to either the health conditions of the occupants, improper location, or poor operation and maintenance conditions.

The relative humidity level is perceived to be acceptable in about 92 percent of the buildings. Only about 8 percent are noticed to be humid as shown in Figure 5.2. A majority of the surveyed occupants have indicated that they are comfortable with humidity levels in their environment as shown in Figure 4.5.

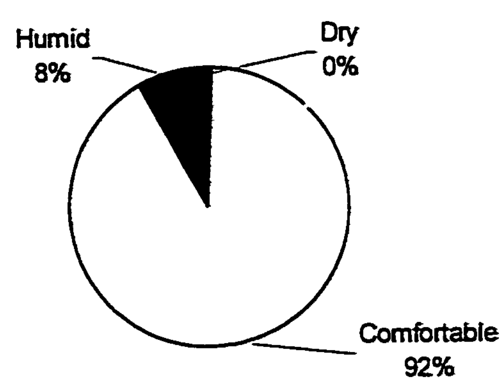


Figure 5.2: Relative Humidity Inspection

The perception of humidity in the inspected buildings could be due to the outside humid air being brought in for the purpose of ventilation. This is an issue of concern in hot and humid climate like the Eastern Province of Saudi Arabia. The humid environment has been observed in the commercial buildings. which could be attributed to the presence of humans in large numbers as well as moisture generating activities or fountains.

The lighting levels in about 96 percent of the inspected buildings were found to be satisfactory as shown in Figure 5.3. This is one of the factors that contribute to overall apprehension of comfort in spaces. About 89 percent of the occupants have reported satisfaction with their lighting environment as shown in Figure 4.7.

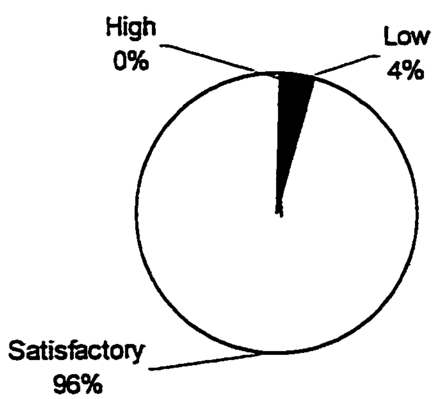


Figure 5.3: Lighting Level Inspection

Stresses from inadequate or poorly designed lighting can cause symptoms like eyestrains and headaches. Lack of sunlight can also be a source of stress. These complaints are sometimes mistakenly interpreted as indoor air quality problems.

The vibration and noise level in all the buildings was found to be satisfactory as shown in Table 5.1. About 46 percent of the buildings demonstrated excellent audible conditions. Almost 73 percent of the surveyed occupants have reported satisfaction with their acoustical environment as shown in Figure 4.6. Noise level is yet another factor that helps in making an environment as comfortable or unbearable. Noisy surroundings can reduce the ability to concentrate and produce stress-related symptoms such as headaches. Low-frequency vibration is another source of stress that may go unreported by building occupants or become confused with pollutant problems.

The other space conditions that were observed during walkthrough inspection are dirt, cigarette smoking, flow of air, and dampness. Their presence. in the investigated buildings, is shown in Figure 5.4.

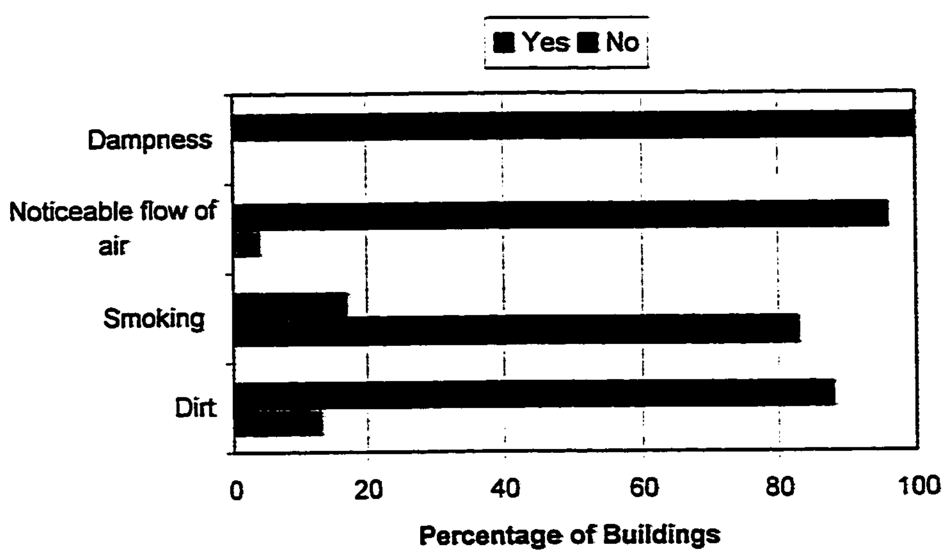


Figure 5.4: Space Conditions in Inspected Buildings

It was observed that most of the spaces were clean of dirt. However, cigarette smoking was noticed in 83 percent of the inspected buildings, which is quite alarming. The conditions are worse in case of commercial buildings. The flow of air was observed to be moderate and that there was no noticeable flow of air as shown in Figure 5.4. Dampness too was not observed in any of the buildings.

5.2.2.2 Ductworks

The condition of ductwork is inspected, as these are the major pollutant pathways. Poorly designed and maintained ducts can add pollution. The presence of moisture in the ductwork could encourage microbiological growth that results in building related illness. It was observed that outside fiberglass duct lining is used in all the inspected buildings as illustrated in Figure 5.5. This confirms the designer's practice of specifying fiberglass insulation as shown in Figure 3.11.

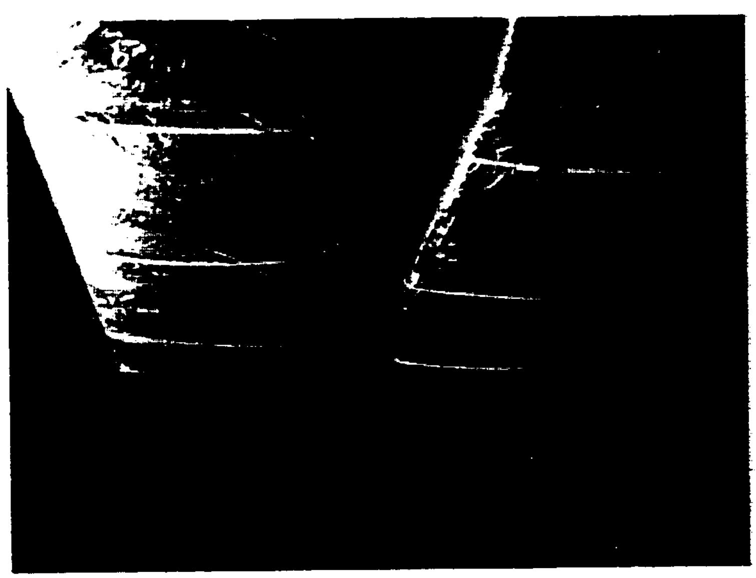


Figure 5.5: Externally Insulated Ductwork

If the problem is of dust accumulation, these outside lined ducts could be easily cleaned. However, if there is mold growth on the fiberglass itself, then it cannot be effectively cleaned and needs replacement. Insulation on the inside of the duct reduces noise but promotes mold growth.

Various factors related to ductworks in the inspected buildings is shown in Figure 5.6. The layouts of air distribution were adequately designed to ensure comfort to all areas of the space. Return air plenum was used in about 92 percent of the cases. These include air-conditioning units with a small return plenum connected to the machine. Only at few places, no return air plenum was used and the mechanical rooms served that purpose. Information is gathered from the maintenance personnel wherever the access is either difficult or impossible.

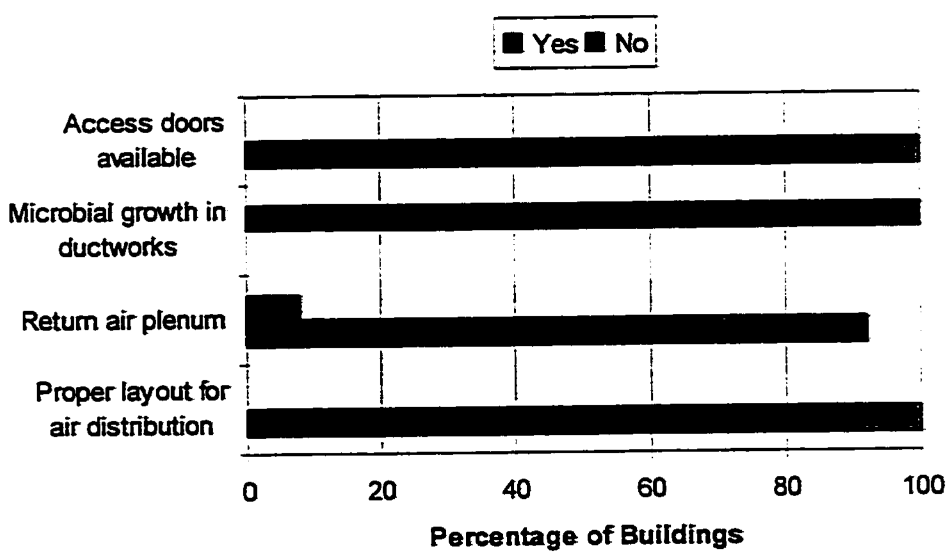


Figure 5.6: Ductwork Condition in Inspected Buildings

There were no indications of the microbial growth in ductworks. One of the main reasons for this could be the outside lining of ductworks, thus reducing the chances for fiberglass insulation to facilitate mold growth. Access doors are available for maintenance and inspection in almost all buildings.

5.2.2.3 Cooling Coils

Cooling coils are one of the potential places for indoor air quality problems in the HVAC system. This is because of the availability of condensed water at this junction. Both air and water systems have condensate drain pans that are designed into the air handling or fan coil equipment to collect moisture from the cooling coil. This is then drained to the sanitary sewer system. The problem for moisture collection could be prominent in high humidity areas and with older systems. It is vital to include cleaning of these condensate drain pans and note any evidence of algae or biocontaminant buildup. Negligence in adequate maintenance and inspection strategies could seriously hamper the indoor environment. Figure 5.7 shows the result of cooling coil inspection in the buildings under investigation.

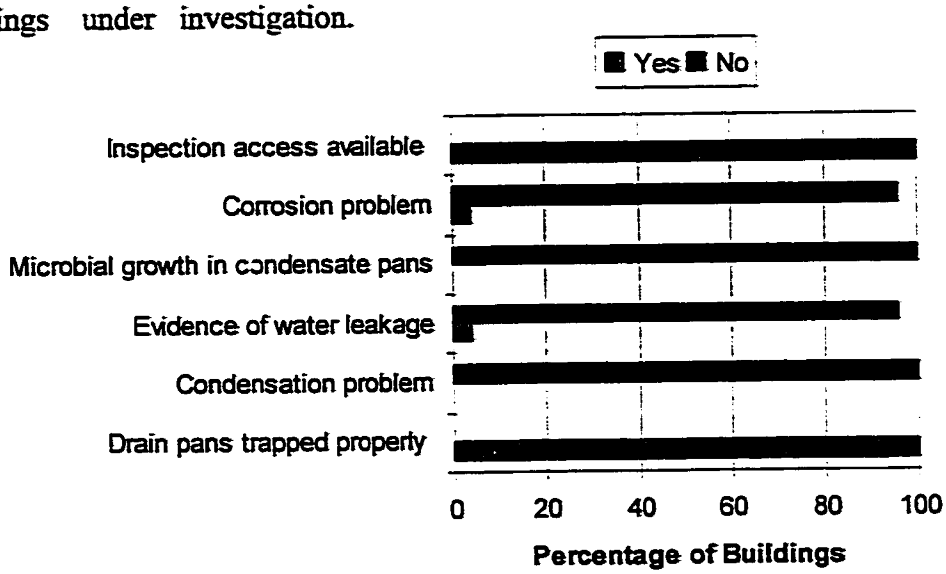


Figure 5.7: Cooling Coils in Inspected Buildings

All the drain pans are trapped properly with adequate piping connections and proper slope from the condensate pan to the drain location. Figure 5.8 illustrates the good and bad cooling coil conditions. There was no serious condensation problem noticed in any of those buildings. However, minor water leakage and corrosion (see Figure 5.8d) has been detected in just 4 percent of the old office buildings. Condensate pans were checked for microbial growth, but none displayed any grim problem.

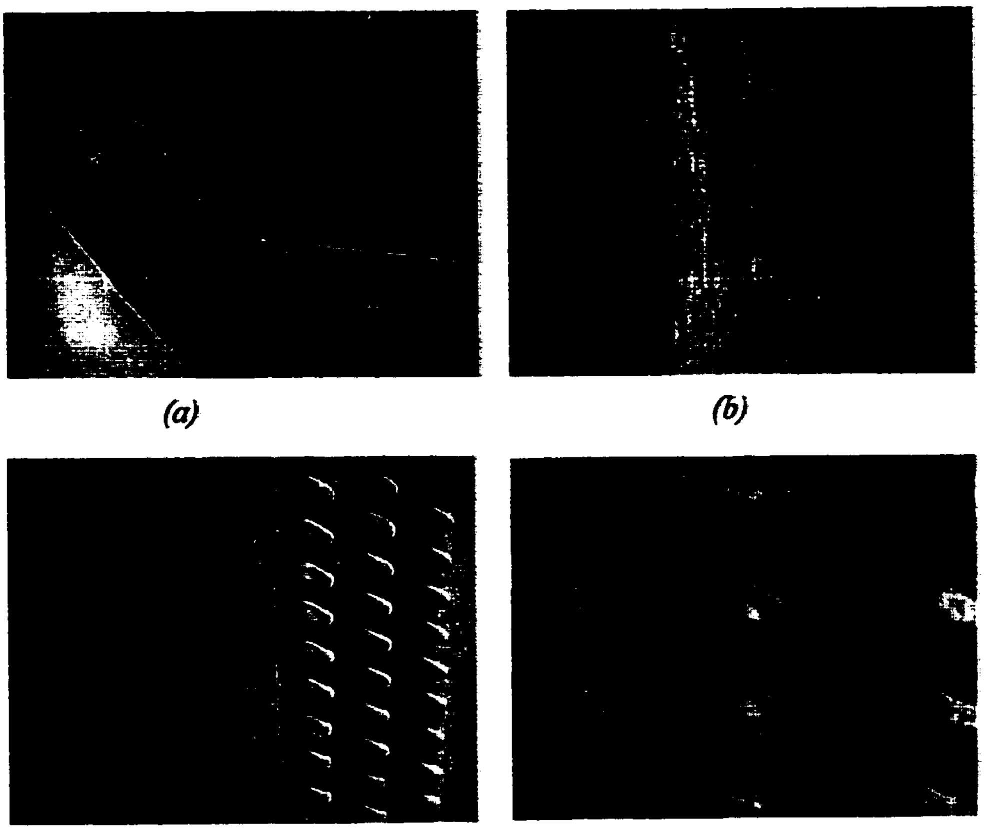

(a) (b) (c) (d)

Figure 5.8: Cooling Coil in Good (a & b) and Bad (c & d) Conditions

Excessive amount of water accumulation in the drain pan of cooling coil could have indicated inadequately sized HVAC equipment. Satisfactory performance of the cooling coils could be due to better maintenance policies or new air-conditioning equipment.

5.2.2.4 Filters

Air cleaning can result in valuable and cost effective tactics to achieve and maintain an acceptable environment. Air filters are basically installed to remove the particulate from air-stream. They are designed and installed depending upon the size and characteristic of the pollutants to be removed. As can be seen in Table 5.1, media filters (shown in Figure 5.9) are found to be the most common type of filters in commercial and office buildings.

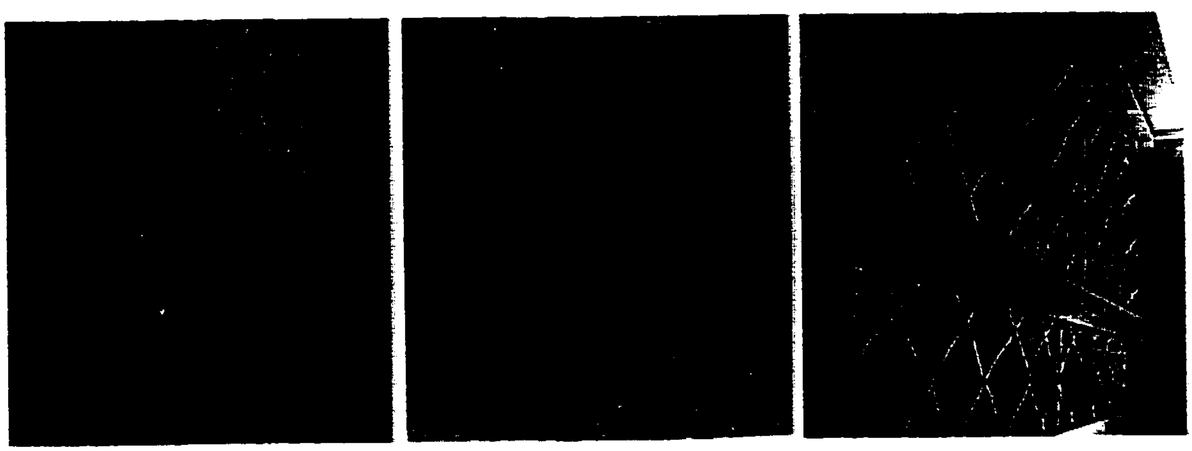


Figure 5.9: Typical Media Filters

About 75 percent of the surveyed HVAC designers have reported of specifying media filters for these types of buildings, as shown in Figure 3.9. Media filters are much finer with high efficient filter paper in pleats within a frame. They work both by straining and impaction. These filters need regular maintenance otherwise they become blocked and damage the HVAC equipment (Stein and Reynolds, 1992).

Figure 5.10 illustrates the condition of filters in the inspected buildings. The filters were in good shape in about 92 percent of the buildings. This is an indication of either the good maintenance practice or the absence of dust and dirt in the surroundings. Filters were in bad condition in some of the old office buildings where no proper maintenance strategies were implemented.

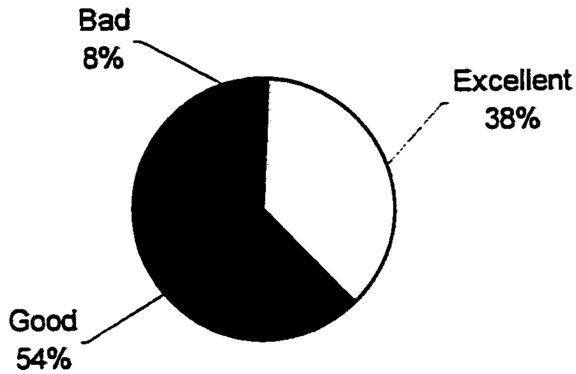


Figure 5.10: Condition of Filters in Inspected Buildings

There were no indications of moisture buildup in the filters of the inspected HVAC systems as can be seen in Table 5.1. The filters, in these units, are located before the cooling coils, which prevent the cooling coils from early degradation and enhances performance. Inspection and maintenance access is available in all these units.

The frequency of cleaning of filters in the inspected buildings, as indicated by the maintenance and operational personnel, is shown in Figure 5.11. As illustrated, the maintenance personnel reported that filters are cleaned after every two to three months. These constitute about 80 percent of the inspected buildings. Others have reported that the maintenance and cleaning of filters is done once or twice a year.

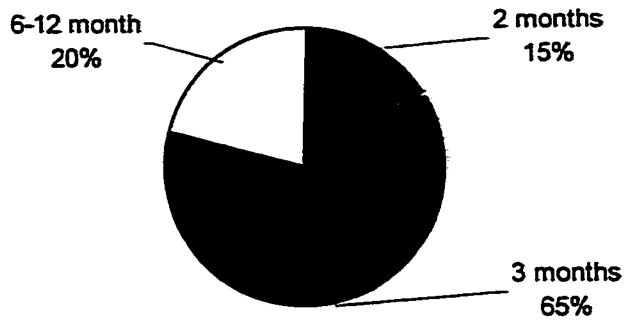


Figure 5.11: Frequency of Cleaning

5.2.2.5 Fresh Air Intake

Outside air intake is also one of the potential causes for air quality problems wherein contaminated outside air enters the buildings via fresh air intake openings and mixes with the building return air and is distributed through the building by the supply air ductwork. Hence, it should be designed in such a way that this polluted outside air cannot enter the building. Some building codes specify that these intakes be located at least 25 feet from any building exhaust or any other external contaminant source.

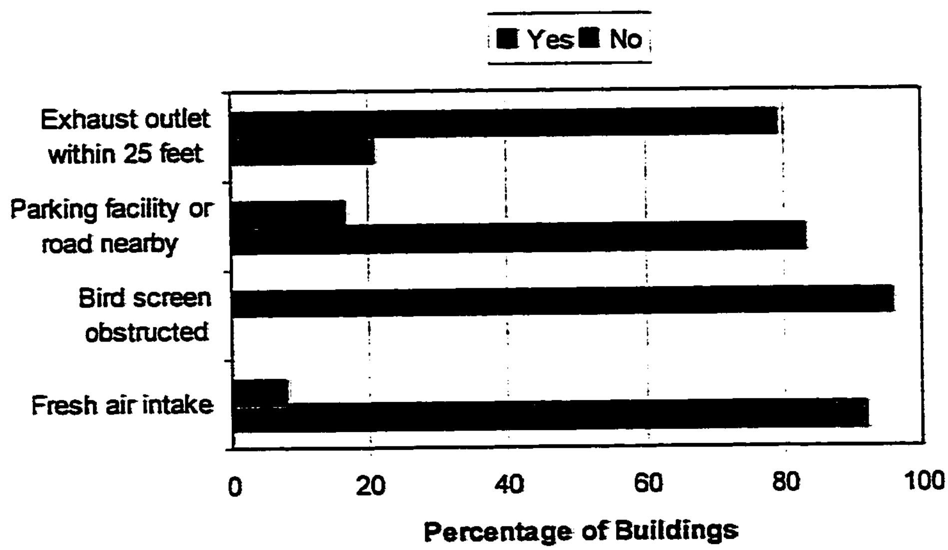


Figure 5.12: Fresh Air Intake Considerations in Inspected Buildings

Figure 5.12 shows the various factors that were checked during the walkthrough inspection. It was observed that the fresh air intake provisions are available in about 92 percent of the buildings. Others use the doors and windows for the outside air intake. Wire mesh or bird screens that are usually installed to protect the HVAC system from the introduction of large debris were present in most of the buildings without any obstruction. However a majority of these buildings, that is about 83 percent, is either on the roadside or near a parking facility. It was also noticed that about 79 percent of the air intake provisions are within the 25 feet of the exhaust, which may reintroduce the contaminated air into the building. The HVAC designers have indicated that they give due consideration to the location of air intakes, bird screen/mesh, and outdoor air quality as shown in Figure 3.13.

5.2.2.6 General Conditions

The general conditions that were inspected during the inspection process includes the exhaust system, separate smoking areas, door tightness, mechanical room conditions, conditions of controls, maintenance and inspection schedules, and contaminant generation area, as shown in Appendix D. This presents an overview of the factors that may have an impact on the performance of HVAC systems and IAQ.

The mechanical room conditions were found to be excellent in about 29 percent of the inspected buildings and satisfactory in around 50 percent of the buildings as illustrated in Figure 5.13.

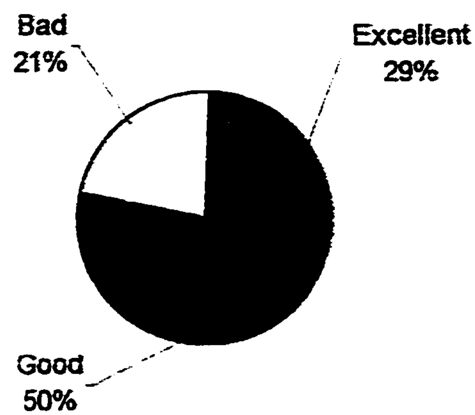
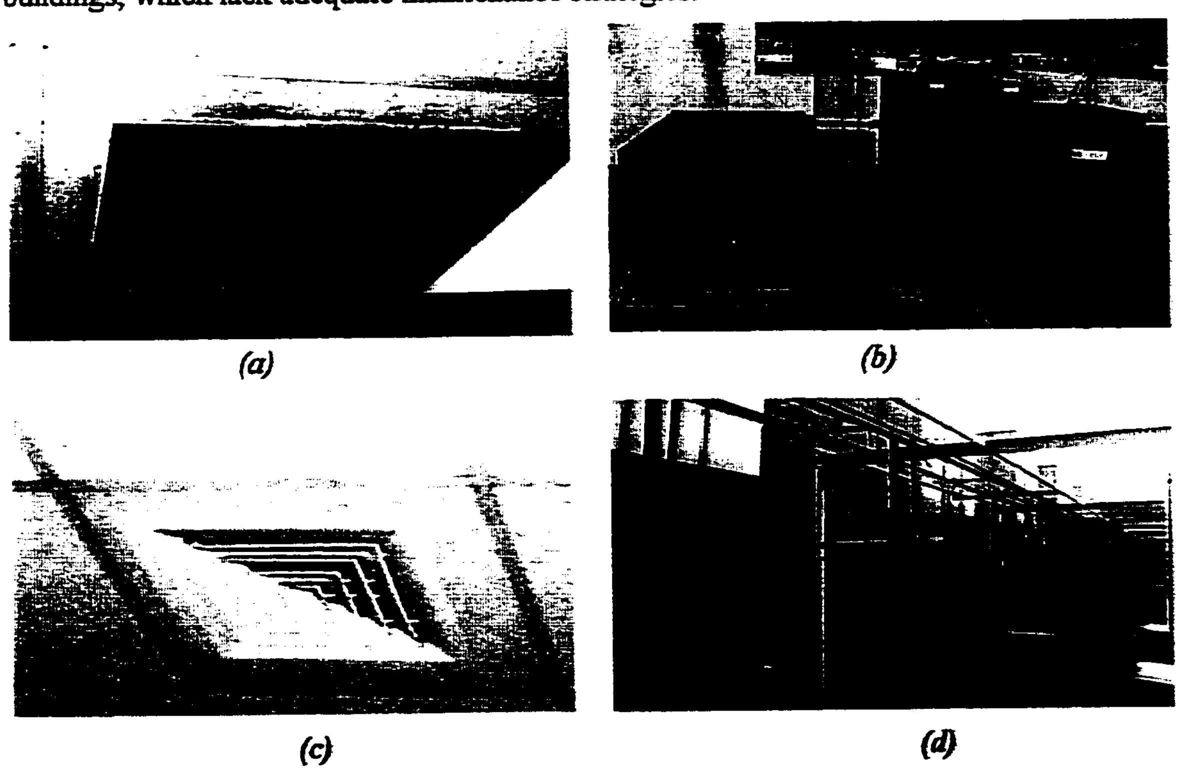


Figure 5.13: Mechanical Room Conditions in Inspected Buildings

However, in 21 percent of the buildings, these places were not properly maintained as shown in Figure 5.14 (a & b). There were obstructions in some mechanical rooms and some were too small. These were mainly old office buildings, which lack adequate maintenance strategies.



(a) *(b)* *(c)* *(d)*

Figure 5:14: Maintenance Practice, Poor (a & b) and Good (c & d)

Figure 5.14 (c & d) illustrates sound maintenance practice, mostly found in commercial and new office buildings. In commercial buildings, there are many types of special use areas such as toilets, print rooms, smoking areas, garage and parking areas that have a potential for creating poor IAQ. Therefore it is highly recommended to install the exhaust fans for these areas. The inspected buildings were checked for the central exhaust system and it was found that in about 38 percent of the cases they are present. There were no separate smoking areas with local exhaust in existing inspected buildings as shown in Figure 5.15. However, the HVAC designers' survey have indicated that about 53 percent of them do allocate separate smoking areas with local exhaust as illustrated in Figure 3.12.

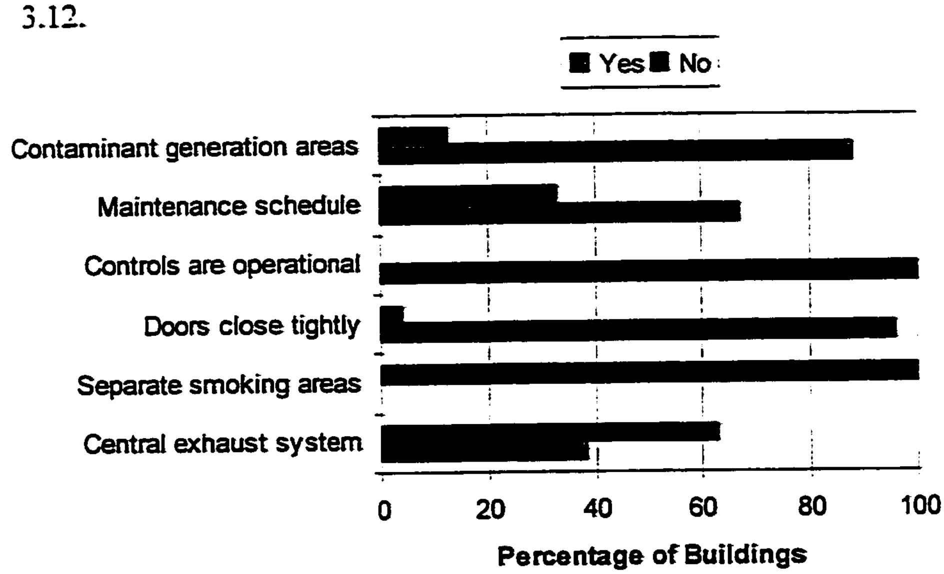


Figure 5.15: General Conditions in Inspected Buildings

Doors to buildings close tightly in about 96 percent of the cases. In other 4 percent of buildings, the doors are used as natural ventilation, which provide the fresh air. The controls, mainly the thermostats were found to be functioning properly in almost all the buildings. Improperly functioning control systems can increase the HVAC system's energy consumption as well as IAQ problems. It was also observed that there are proper maintenance and inspection schedules adopted in these buildings which is essential for any space to remain healthy. As mentioned earlier, NIOSH has reported HVAC systems to be the cause of over 50 percent of all IAQ problems and complaints (Hays. et. al., 1995). Therefore its maintenance is vital to the operation of healthy buildings and its absence can risk of creating sources of contamination with the HVAC system.

It was noticed that a majority of the inspected buildings, about 88 percent have contaminant generation areas within them. These includes the presence of cigarette smokers, kitchen, toilet, photocopy machines, printers and plotters. etc. The most severe problem was observed in commercial and old office buildings where a large number of cigarette smokers were present. This is even observed in new office buildings but on a lesser scale. The areas with contaminant generation should be maintained at negative pressure in relation to adjacent areas to prevent the migration of the polluted air.

5.3 Measurements

Certain air quality measurements that are indicative of common IAQ concerns, such as temperature, relative humidity, and carbon dioxide have been taken. Most of the previous investigations for indoor air quality have also involved the measurements of temperature, relative humidity and carbon dioxide (Gan, 1994., Grot, 1991., and Collett, 1993). These measurements help to establish baseline conditions that could be compared with standards, or with outdoor air quality, or to reveal the existence of compounds associated with particular types of building problems. However, there are other contaminants like carbon monoxide, sulphur dioxide, formaldehyde, etc. which have not been measured due to constraints in time and resources. As mentioned earlier, a total of forty buildings were initially selected for the study, however measurements were carried out in twenty-four buildings based on the type of HVAC system used and the ease of accessibility.

5.3.1 Conducting the Measurements

Instrument measurements were carried out to assess the existing status of IAQ in all the 24 selected commercial and office buildings. The following parameters were monitored to indicate the general performance of the HVAC systems:

(i) carbon dioxide which is a useful general indicator of the adequacy of the outdoor air supply and IAQ, measured with portable CO_2 analyzer

(ب) temperature and relative humidity as indicators of thermal comfort, measured with a quick response electronic multifunctional environmental instrument.

Proper operation and calibration of measuring instruments are critical to the success of any sampling program. Calibration to ensure accurate measurements is done using standard procedure for all instruments. Direct-reading instruments have been used to gather data at different locations. These locations include places near the supply air diffuser, return air diffuser, a central location in the room, and an outdoor site adjacent to the HVAC system air intakes. These locations are selected to reflect different uses of a space and the role HVAC systems play in improving or deteriorating the IAQ. These measurements were generally recorded at the peak time of occupancy. It was also ensured that these measurements are taken at least two hours after the space has been occupied.

The carbon dioxide concentration is measured with a versatile infrared carbon dioxide gas analyzer, model GD444 of CEA Instruments Inc. A multifunctional environmental instrument, MPM 500e of Solomat Instrumentation has been used to measure temperature and relative humidity.

5.3.2 Measurement Analysis

The following section deals with the analysis of the measurements undertaken to record the environmental parameters of temperature, relative humidity, and CO_2 that are indicative of the comfort conditions in spaces.

5.3.2.1 Temperature

Recommended range of indoor air temperature is dependent on the season. They typically range from 20°C to 23°C for the winter and from 23°C to 26°C for the summer. Table 5.2 shows the recorded air temperature in the conditioned space and the outdoor air during the months of February and March. It can be observed that the room temperature range for new office buildings is between 22°C to 26°C, for old office buildings the range is between 20°C to

25°C, and for commercial buildings it is between 22°C to 26°C. Hence all the buildings are within the thermally comfortable range, except for some old office buildings which has slightly lower temperatures. The outdoor temperature ranges from 23°C to 31°C during these measurements period.

Table 5.2: Recorded Temperature (°C) in Investigated Buildings

Building Type	Building Number	Outdoor Air (deg.C)	Room Air (deg.C)
New Office Buildings	1	23.2	25.7
	2	29.7	22.8
	3	26.6	25.7
	4	26.4	24.5
	5	26.1	23.6
	6	26.1	23.5
	7	26.3	22.1
	8	25.8	24.6
Old Office Buildings	1	24.8	25.2
	2	28.6	21.0
	3	26.0	24.8
	4	30.5	23.8
	5	28.1	23.0
	6	23.7	20.6
	7	23.6	24.7
	8	23.8	24.2
Commercial Buildings	1	25.3	24.2
	2	28.6	25.8
	3	26.4	23.5
	4	25.1	23.5
	5	25.1	24.6
	6	25.1	24.7
	7	27.1	26.2
	8	25.2	22.4

5.3.2.2 Relative Humidity

The relative humidity level of 50 percent is least hospitable to contaminants. However, productivity and performance are at its best with 30 to 60 percent RH. The relative humidity that was recorded in various commercial and office buildings is shown in Table 5.3. It can be observed that the relative humidity in new office building range from 31 to 56%, for old office buildings it ranges from 39 to 61%, and for commercial buildings it ranges from 37 to 66%. The relative humidity was well within the comfort zone for most of the investigated buildings. The measured relative humidity for outdoors ranges from 27 to 67%.

Table 5.3: Recorded Relative Humidity (%) in Investigated Buildings

Building Type	Building Number	Outdoor Air (%RH)	Room Air (%RH)
New Office Buildings	1	36.0	31.4
	2	40.8	52.7
	3	36.7	55.3
	4	30.1	44.1
	5	35.4	51.5
	6	35.4	51.9
	7	38.4	55.3
	8	36.8	54.6
Old Office Buildings	1	57.3	55.5
	2	27.6	42.0
	3	34.6	49.5
	4	46.2	60.9
	5	31.5	47.4
	6	39.9	41.7
	7	46.5	39.1
	8	38.7	48.4
Commercial Buildings	1	38.6	65.4
	2	28.8	47.6
	3	30.1	47.3
	4	36.5	37.2
	5	36.5	51.6
	6	36.5	43.8
	7	67.2	52.4
	8	50.9	46.4

Figures 5.16 to 5.18 show the conditions of the investigated buildings on the ASHRAE psychrometric chart. The measured temperature and relative humidity in the investigated buildings have been shown on these charts. It is encouraging to see that most of the surveyed office and commercial buildings are well within the ASHRAE comfort zone as shown in Figure 2.6.

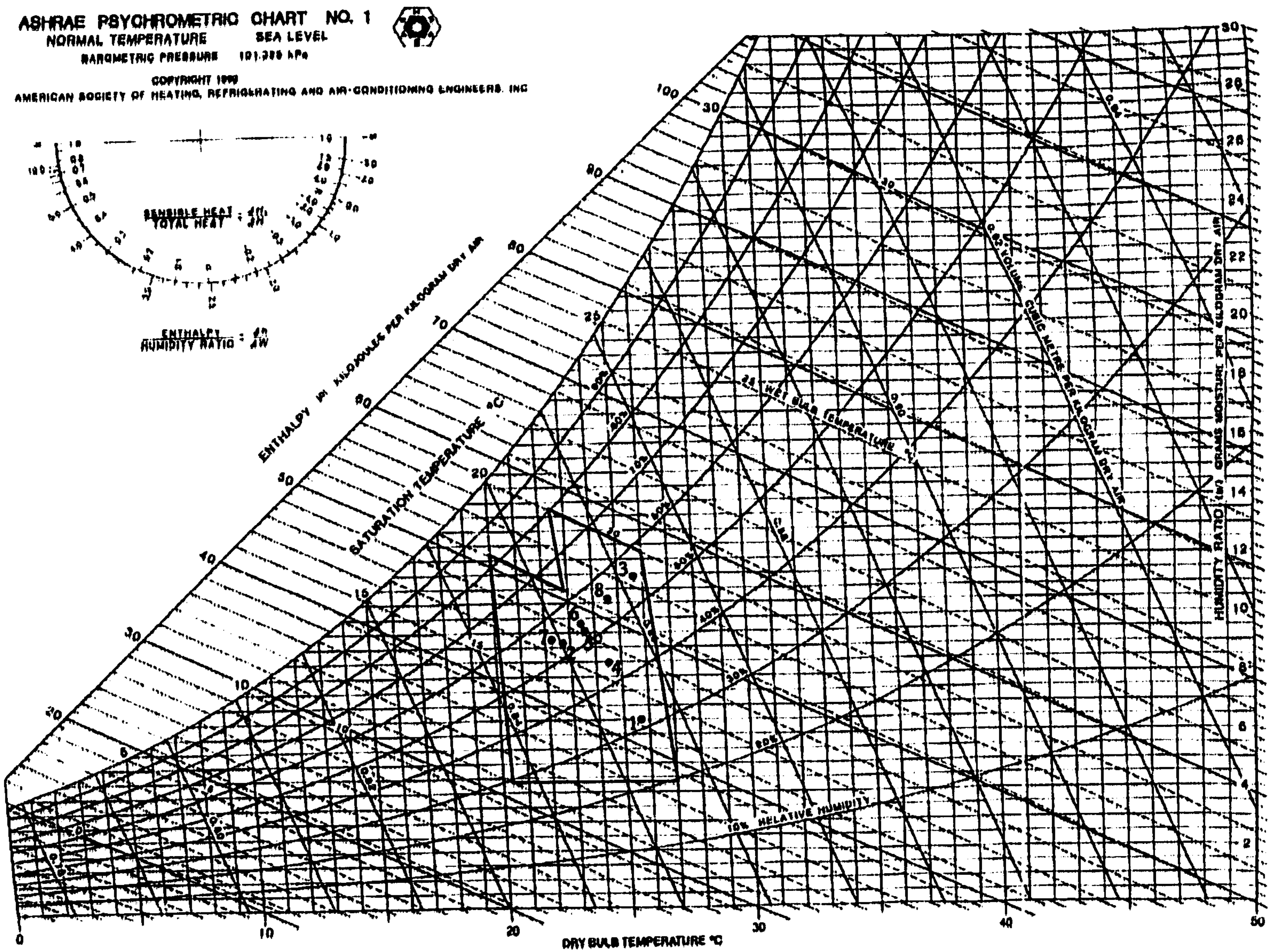


Figure 5.16: Comfort Conditions in New Office Buildings

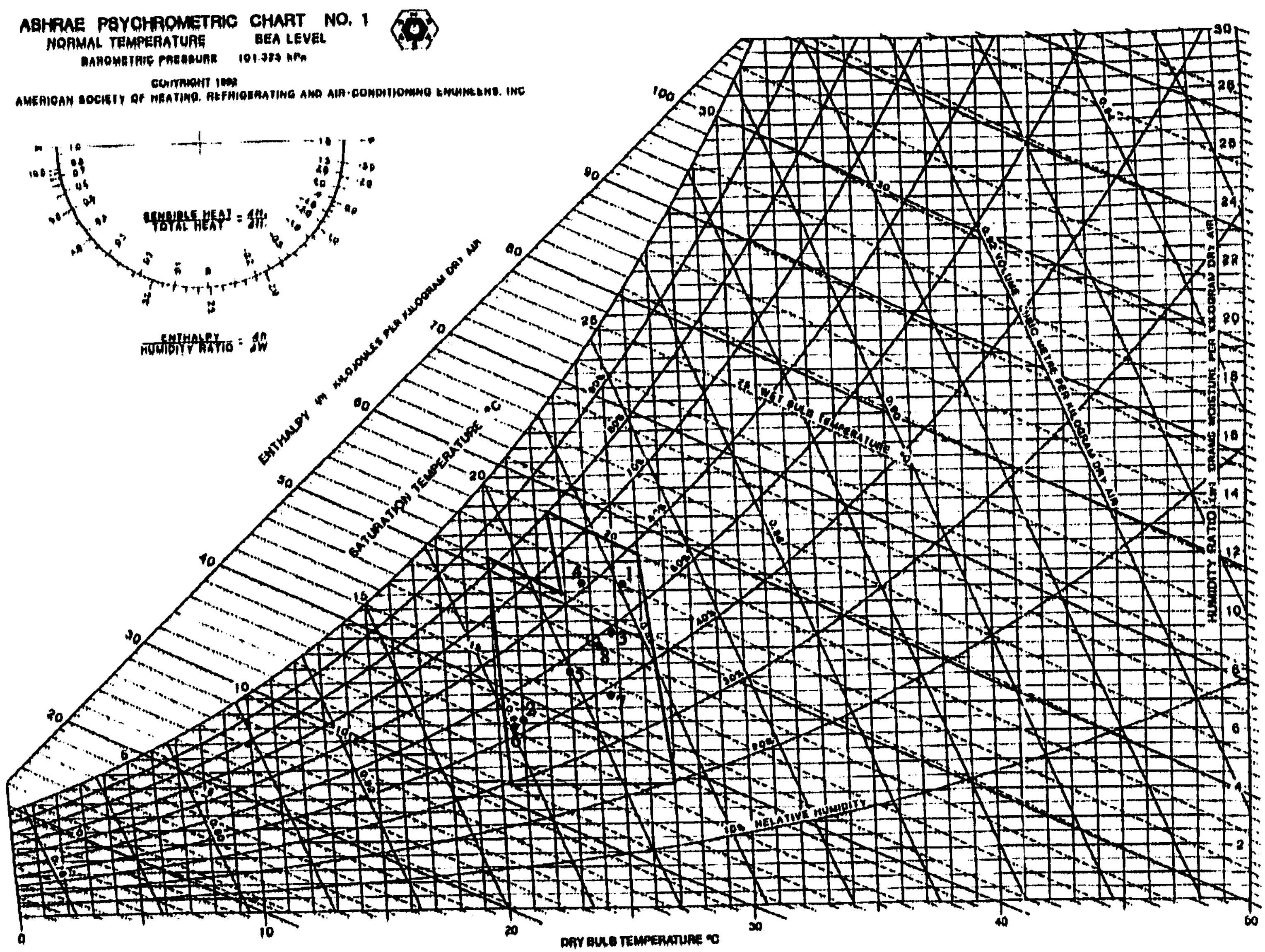


Figure 5.17: Comfort Conditions in Old Office Buildings

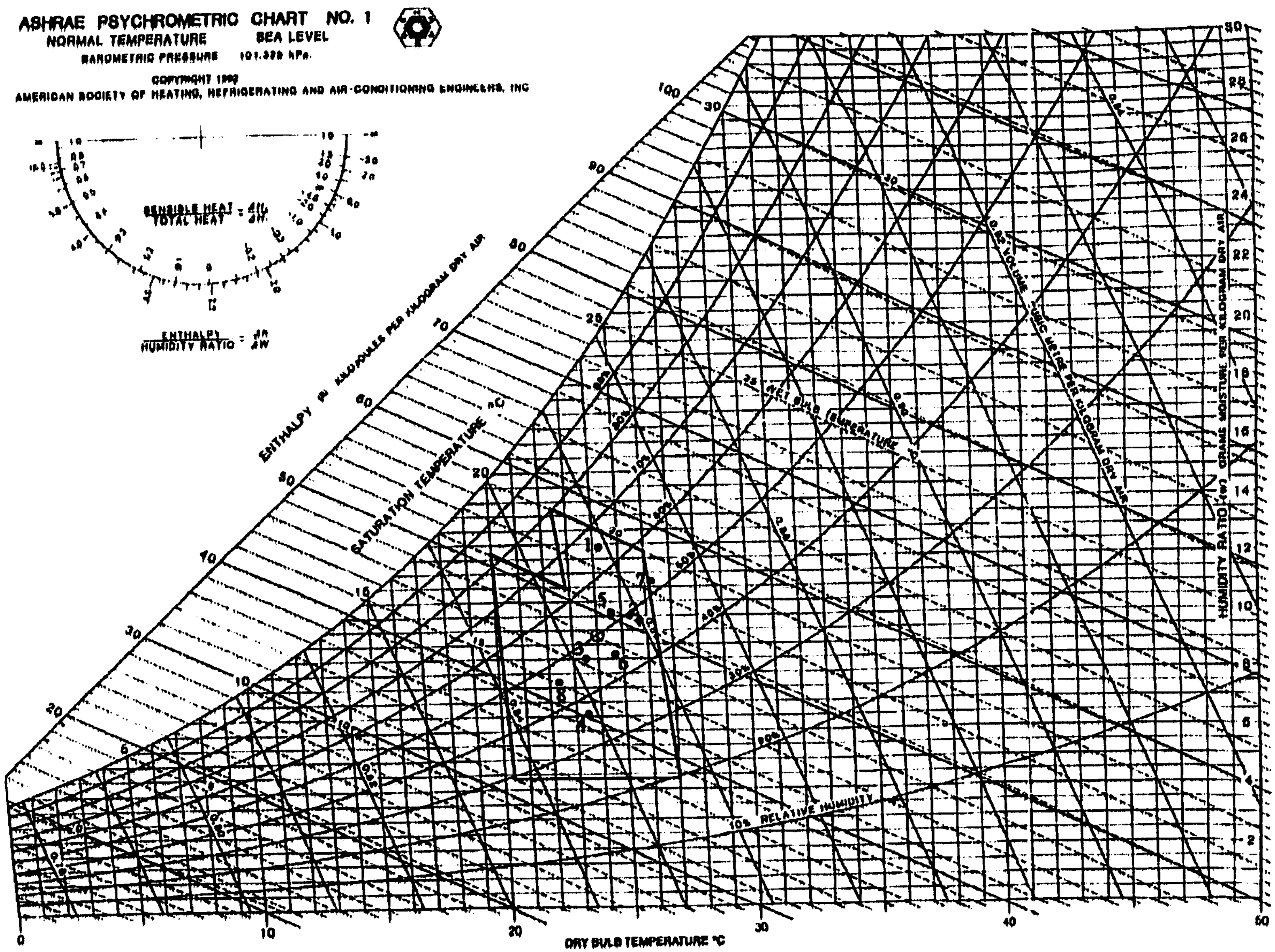


Figure 5.18: Comfort Conditions in Commercial Buildings

5.3.2.3 Carbon Dioxide Concentration

Table 5.4 presents the recorded carbon dioxide concentrations levels in investigated commercial and office buildings.

Table 5.4: Recorded CO_2 Concentration (ppm) in Investigated Buildings

Building Type	Building Number	Outdoor Air (ppm)	Room Air (ppm)
New Office Buildings	1	330	380
	2	370	660
	3	340	540
	4	300	410
	5	300	600
	6	300	590
	7	440	720
	8	430	750
Old Office Buildings	1	370	1390
	2	340	890
	3	280	1100
	4	440	780
	5	340	640
	6	320	380
	7	330	540
	8	320	570
Commercial Buildings	1	430	930
	2	320	870
	3	330	860
	4	340	760
	5	300	720
	6	340	1140
	7	320	520
	8	330	620

Normally, outdoor ambient concentration of CO_2 are in the range of 250 to 350 parts per million (ppm) and indoor levels are less than 1000 ppm. The CO_2 level of the outdoor air is within the range of 280 to 440 ppm, but in most of the cases it ranges from 320 to 340 ppm. The level of CO_2 inside the old office buildings was observed to be in the range of 380 to 1390 ppm. In new office buildings it was between 380 to 750 ppm, and in commercial buildings it was recorded between 520 to 1140 ppm. Two buildings among investigated old office buildings and only one commercial building have crossed the acceptable limit of 1000 ppm. One of the reasons for acceptable range of CO_2 concentration could be due to the good amount of fresh air entering the buildings. However, there could still be problems related to IAQ, like the presence of some strong contaminant source that requires control, as CO_2 is just one of those contaminants that was measured. Other contaminants like CO, formaldehyde, volatile organic compounds, etc. have not been measured. Higher values of CO_2 in some spaces could be due to reasons like increased occupancy level, poor air distribution, or poor air mixing.

5.3.2.4 Percentage of Outdoor Air

The percentage of outside air for various investigated buildings is shown in Table 5.5. This was estimated by measuring the CO_2 concentration in supply air (SA), return air (RA), and outside air (OA) according to the equation (Hays. et. al. 1995):

$$OA\% = \frac{CO_2 \text{ level in } RA - CO_2 \text{ level in } SA}{CO_2 \text{ level in } RA - CO_2 \text{ level in } OA} \times 100$$

Table 5.5 shows the percentage of outdoor air being taken inside the building to compensate for the exhaust air or to dilute the contaminants that are present inside the building. The measurements were normally conducted during the peak occupancies in the morning and afternoon hours. It should however be made clear at this point that it needs longer period of CO_2 monitoring than has been done in this project due to constraints in time and access to the sites. It should also be noted that the researchers are presently studying ways to measure ventilation efficiency and interpret the results of these measurements (EPA. 1998). The use of CO_2 as an indicator of ventilation is not always accurate because of the variability of CO_2 generation rate of building occupants and the uncertainty as to whether CO_2 buildup in a space or building has ever reached equilibrium (Hays, et. al., 1995).

Table 5.5: Outdoor Air Intake in Investigated Buildings

Building Type	Building Number	Carbon Dioxide Concentration (ppm)				Percentage of OA
		Outdoor Air	Supply Air	Return Air	Room Air	
New Office Buildings	1	330	400	430	380	30
	2	370	600	730	660	36
	3	340	480	570	540	39
	4	300	440	460	410	13
	5	300	550	640	600	26
	6	300	540	740	590	45
	7	440	670	730	720	21
	8	430	720	820	750	26
Old Office Buildings	1	370	1280	1420	1390	13
	2	340	840	1040	890	29
	3	280	1170	1330	1100	15
	4	440	700	790	780	26
	5	340	480	540	640	30
	6	320	370	390	380	29
	7	330	470	550	540	36
	8	320	480	580	570	38
Commercial Buildings	1	430	710	880	930	38
	2	320	910	1380	870	44
	3	330	890	1100	860	27
	4	340	570	790	760	49
	5	300	540	650	720	31
	6	340	1000	1250	1140	27
	7	320	400	440	520	33
	8	330	530	680	620	43

Percentage of outdoor air or fresh air is a calculation of the mixture of outdoor air and air recirculated from the building. The buildings are generally operated with a minimum setting of outdoor air at 15 to 20 percent of the total supply air (Hays, et. al., 1995). CFM per person of outdoor air is obtained by dividing the total quantity of outdoor air being delivered to the number of people present. The percentage of outdoor air entering the space could be converted to cfm of outdoor air using the equation (EPA, 1998):

$$\textit{Outdoor air (in cfm)} = \frac{\textit{Outdoor air (percent)}}{100} \times \textit{Total airflow (cfm)}$$

It was observed that the percentage of fresh outside air being taken in the new office buildings ranged between 13 to 45 percent, in old office buildings between 13 to 38 percent, and in commercial buildings it was between 27 to 49 percent. In general these values seems to be higher, but it could be attributed to many reasons like more fresh air was being taken in because of pleasant weather conditions, or to compensate for high occupancy level, or it could be because of the instrument itself as it is highly sensitive to the presence of humans around its probe, etc.

5.4 Summary

This section presents the summary of walkthrough inspection and instrument measurements that were carried out in commercial and office buildings. As stated earlier, the objective of the inspection was to acquire an overview of the existing conditions prevailing in those buildings. Instrument measurements were carried out to gauge the magnitude of the conditions.

In general, it has been observed that the new office buildings have better maintenance and inspection schedules as compared to others. Even there were no abnormal odor perceived in these spaces.

The temperature, relative humidity, lighting levels, and noise levels were within the acceptable range with a little percentage of dissatisfaction as shown in Table 5.1. These factors are decisive in making a comfortable environment. Even there was no noticeable flow of air or dampness in most of these buildings. However, a severe problem of cigarette smoking has been observed in all types of buildings, especially in commercial and old office buildings. This is an issue of concern as the contaminants are released into the living space and contains many carcinogenic, teratogenic, and mutagenic chemicals in the smoke.

The ductworks are in good conditions in general. The duct lining consist of outside fiberglass insulation in most cases. Inside insulation is generally applied to reduce the noise at the mouth of air-handling unit, but it creates IAQ problems by aiding the growth of microbial organisms. There was no evidence of microbial growth inside the ducts in inspected buildings. The layout of air distribution system was appropriate, in most of the buildings, that covers all corners of the space. Proper layout of air distribution system is important because the airflow patterns that are created from the location of supply and return air grilles in the occupied space affect thermal comfort.

The condition of the cooling coils were also found sound. There was no major condensation problem noticed in any of the buildings neither there was any evidence of the microbial growth in the condensation pan. Excessive water accumulation in this section usually results in mold growth. The condensate drain pans were properly trapped, and sloped to the drain locations. The inspection access is available and corrosion was rarely seen in these buildings. Corrosion was observed in some of the old machines in old office buildings.

Media type filters are the most commonly used filters in these types of buildings. Most of these filters were found to be in good condition. However few of the old office buildings have filters in bad condition as well. These buildings do not have a maintenance and inspection schedule. There was no indication of abnormal moisture buildup on filters. The presence of moisture on filters could deteriorate the IAQ as it helps in the growth of microorganisms. The filters, in general, are located before the cooling coils. This will prevent the dust and dirt to come in direct contact with the cooling coil which may cause damage. The filters are maintained and cleaned two to three times a year in most of the new office and commercial buildings, where as it is carried out once or twice annually in old office buildings. The inspection and cleaning access are available.

Fresh air intakes are available in most of the inspected buildings as shown in Table 5.1. ASHRAE requires a minimum ventilation rate of 15-20 cfm per person to compensate for losses due to exfiltration and for the sake of circulating fresh air. This is sometimes a major cause of IAQ problems as the outside-polluted air enters the conditioned space through these outside air intakes. These intakes are usually provided with a mesh or a bird screen to prevent large debris from entering. These bird screens were not obstructed.

Parking facility or roads are nearby in about 83 percent of the buildings. Some building codes specify that these intake locations should be about 25 feet from any building exhaust. It was observed that about 79 percent of the inspected buildings have fresh air intakes within 25 feet distance from building exhaust.

It was noticed that the maintenance and inspection schedule is available in 67 percent of the inspected buildings. Others do not have a fixed schedule, they rather rely on feedback from occupants to correct the problem. The controls are in good operating conditions. There were no separate areas for tobacco smoking with local exhaust. Rather it was observed that the smokers are smoking indiscriminately in all areas. This air is circulated and recirculated in the occupied space, which hampers the IAQ. Most buildings have contaminant generation areas in them, like the presence of smokers, toilets, kitchen, etc. However, a majority of them doesn't have a central exhaust system.

Instrument measurements were carried out to record temperature, relative humidity, and CO_2 concentrations. These measurements were undertaken in peak occupancy conditions. It was encouraging to find that most of the investigated buildings were within the ASHRAE comfort zone, which means that the temperature and humidity in these spaces are within the comfort zone, as shown in Figure 5.16 to Figure 5.18. CO_2 concentration was below the limit of 1000 ppm in most of these spaces. Percentage of outdoor fresh air entering the building is also estimated. Since the measurements were carried out for a short period of time, the results are an indication of the overall conditions of spaces.

CHAPTER 6

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

This research study has been carried out in different phases that includes HVAC designer's survey, building occupant's survey, and field survey. Initially, a comprehensive literature review has been carried out on issues related to IAQ and HVAC systems. In Chapter 3, the acquired design information from the HVAC designers in the Eastern Province of Saudi Arabia has been presented. In all, thirty-two HVAC design offices participated in the study to establish their general design practice. 24 buildings were finally selected for the study based on the type of HVAC system employed, size of building, and the ease of accessibility. Occupant's questionnaire survey has been conducted in these buildings to determine occupant's level of satisfaction with the environment. In all, 504 filled in questionnaires were received from the occupants of these buildings. The comfort questionnaire responses from the building occupants have been discussed in Chapter 4. This was followed, in Chapter 5, by a discussion on the field survey, which consisted of walkthrough inspection and measurement of environmental and CO_2 parameters.

It was evident from the literature review that in most cases, IAQ problems are either associated with the HVAC systems or these systems could be a remedy to the problem. The major problems associated with the HVAC systems have been identified as inadequate ventilation, inside contamination, microbiological contamination, polluted outside air supply, and inadequate filtration. The literature also verifies that the HVAC systems could be the source for some pollutants. But, the extent of the problem and its impact on human health remains undiscovered. The importance of good design, commissioning, operation and maintenance of the HVAC systems is well accepted.

The manufacturers and designers of the HVAC systems were then contacted to know the most commonly used HVAC systems for commercial and office buildings in the Eastern Province of Saudi Arabia. Product literature and specifications were obtained from the major manufacturers and suppliers of these systems. Personal interviews were also conducted with the sales representatives of suppliers. Self-administered questionnaires were distributed to the HVAC designers, inquiring about their design practices. They were asked about the design criteria, ventilation rates, filtration efficiency, range of temperature and humidity, and so on. Other issues and real world cases were discussed during informal interaction. As a result, the most frequently used HVAC systems were identified as rooftop package units, split systems and constant volume systems.

The HVAC designers have indicated that thermal comfort and indoor air quality are the major considerations in their designs. Temperature, humidity, and air speed govern thermal comfort, where as acceptable IAQ is governed by the quantity/quality of outdoor air intake and CO_2 concentration.

The design range of indoor temperature, which is perhaps the most important thermal comfort parameter, is between 22°C and 26°C, which is in accordance with the ASHRAE specified comfort zone. About 88 percent of the investigated buildings have been found to be thermally comfortable during the walkthrough inspection. Almost 87 percent of the occupants, in these spaces, have expressed thermal satisfaction with their environment. The measured temperature in these buildings ranged between 23°C and 26°C. Hence, it could be concluded that a majority of these buildings are thermally comfortable.

The next important parameter that affects the perception of thermal comfort is humidity, which is designed in the range of 45% to 55% by a majority of the surveyed HVAC design engineers. ASHRAE specifies the range of relative humidity over the comfort zone as approximately between 30% and 60%. The measured values for humidity in the investigated buildings range between 35% to 60%. It was observed during the walkthrough inspection that about 92 percent of buildings are maintained at acceptable humidity levels. About 71 percent of the building occupants have expressed satisfaction with the level of humidity present in their spaces. It could be concluded that a majority of these buildings are performing satisfactorily in terms of humidity levels.

There was no noticeable flow of air (draft) during the inspection of investigated buildings. About 96 percent of the occupants have indicated that the air movement is either moderate or still. Too much air movement cause draft, an undesired local cooling of human body, which may result in a demand for higher air temperature or for stopping the ventilation system.

In order to achieve acceptable IAQ, ASHRAE standard 62-1989 specifies a rate of 7-10 L/s (15-20 cfm) per person for office and commercial buildings. Almost 50 percent of HVAC designers have indicated that their preferable rate of ventilation is between 7-10 L/s (15 to 20 cfm) per person. Another 34 percent specify ventilation rate of 5-7 L/s (10 to 15 cfm) per person. An approximate calculation of the percentage of outside air using measured CO_2 concentration has been carried out. This calculation is used by researchers to get an overview of the existing conditions. The quantity of outdoor air in these buildings ranged between 25 to 45 percent. It has to be noted here that these are not the values for cfm per person. Moreover the measurement of CO_2 concentration has to be recorded for a longer duration over a period of time to draw more precise estimation. However, it could be inferred that a good amount of fresh air is being taken inside these buildings. The CO_2 concentration of this fresh air is normally found to be between 280 to 340 ppm.

The HVAC design engineers have suggested that they give due consideration to the maintenance accessibility, proper air distribution systems, and filtration efficiency. During the walkthrough inspection, it was observed in most of the buildings that the ducts are properly distributed and drain pans trapped properly with no significant corrosion problem. It was also noted that there is neither significant moisture buildup nor microbial growth in any of these buildings. In addition, about 85 percent of the occupants have indicated that they are comfortable with their overall building environment.

It has been observed during inspection of the investigated buildings that there are no scheduled maintenance and inspection in about 33 percent of the buildings, and the overall condition of about 21 percent of the mechanical rooms was not good. Maintenance, in these buildings, is carried out either on a fixed period contractual basis or when the system halts functioning. The building occupants have reported that the major problem associated with the HVAC system is that of extreme temperatures, that is sometimes it is either too cold or too hot, and that better control is needed.

The central exhaust system is available only in about 38 percent of the surveyed buildings. However, odor, which is one of the indicator of IAQ problem is perceived by about 29 percent of the occupants. It could be related to the presence of cigarette smoke, which was found to be a major pollutant in about 83 percent of the spaces. Most of the surveyed HVAC design engineers have indicated that they design separate smoking areas for commercial and office buildings. However, the investigated buildings does not have smoking areas

The collected information from the literature review, HVAC designer's survey, building occupant's survey, walkthrough inspection, and instrument measurements have indicated that there were no significant air quality problems in the investigated buildings. The data collected was sufficient to gauge the overall condition of air quality as affected by HVAC systems in these buildings. However, a more elaborate measurement of environmental parameters and other contaminants for a longer duration of time would be helpful in drawing more precise estimation of indoor spaces, which could not be performed in this research due to time and resource constraints.

6.2 Conclusions

The following conclusions have been drawn based on the results of HVAC designer's survey, building occupant's survey, walk-through inspection. and environmental and CO_2 measurements:

1. No significant air quality problems were noticed in most of the investigated commercial and office buildings.
2. The measured values of temperature and relative humidity in the investigated buildings lie within the ASHRAE comfort zone.
3. The most frequently used type of HVAC systems for commercial and office buildings in the Eastern Province of Saudi Arabia were identified as rooftop package units, split systems, and constant volume systems.
4. Carrier, Zamil, and Trane are the most popular HVAC systems manufacturer with the designers, who usually base their selection criteria for manufacturer on either good experience with the product or suitability to weather conditions.
5. The HVAC designers have suggested that "thermal comfort" is their primary design criteria, followed by the IAQ considerations and energy conservation.

6. The design range of indoor air temperature is between 22°C and 26°C. Measured values of temperature in investigated buildings ranged between 23°C to 26°C. Both these design and measured values of temperature lie within the ASHRAE specified comfort zone. 87 percent of the surveyed occupants have expressed thermal satisfaction with their environment. 88 percent of surveyed buildings were found to be thermally acceptable during walk-through inspection.
7. The design range of relative humidity is between 45% to 55%. Measured values of relative humidity in these spaces ranged between 35% to 60%. Both these design and measured values of relative humidity lie within the ASHRAE specified comfort zone. 92 percent of spaces were found to be maintained at acceptable humidity levels. 71 percent of occupants have expressed their satisfaction with the humidity levels in their spaces.
8. Only about 9 percent of the surveyed HVAC designers have indicated that they specify ventilation rates of less than 5 L/s (10 cfm) per person. However, a majority of surveyed designers specify ventilation rate of 7-10 L/s (15-20 cfm) per person, confirming to ASHRAE standards.
9. The level of CO_2 concentration, which serves as a suitable surrogate measure of IAQ, in most of the investigated spaces was found to be less than 1000 ppm which is the maximum permissible level recommended by EPA.
10. The lighting levels were found to be satisfactory in almost all the investigated buildings during walk-through inspection. About 89 percent of building occupants have expressed their satisfaction with lighting levels in their spaces.

11. The background noise levels, in these buildings, were also found to be satisfactory during walk-through inspection. Almost 74 percent of occupants have expressed their satisfaction with the noise levels in their spaces.

12. The air movement in most of these spaces was observed to be moderate with no signs of draft or dirt. About 96 percent of building occupants have expressed satisfaction with the air movement, and almost 90 percent of occupants have termed the air as "clean".

13. About 54 percent of building occupants have reported perceiving slight to moderate odor in their work environment. This could be due to cigarette smoking, which has been found to be a major pollutant source in most of these spaces.

14. Almost all of the surveyed HVAC designers specify external fiberglass insulation to ductworks. These ductworks are properly distributed to ensure air supply to all parts of the space. Return air plenum was used in most of the buildings.

15. The cooling coils are generally in good conditions in these buildings with no significant problems of condensation or corrosion. The HVAC designers give due consideration to properly drain the water.

16. Media filters are the most common types of filters. About 75 percent of the surveyed designers specify them for commercial and office buildings. Most of the filters were found to be in good conditions.

17. The HVAC design engineers give due consideration to the location of outdoor air intake, bird screens, and outdoor air quality. The exhaust outlets were normally found to be away from these fresh air intakes.

18. It has been noted that there was no proper maintenance and inspection schedule in some of the investigated buildings. It was either done on a contractual basis or as breakdown maintenance. This has resulted in poor condition of some filters and improper mechanical room conditions in those few buildings.
19. Cigarette smoking was observed in most of the buildings. However, there was no separate smoking areas with 100 percent exhaust.

6.3 Recommendations

There were no major IAQ problems found to be associated with the HVAC systems in the investigated commercial and office buildings in the Eastern Province of Saudi Arabia. However, there are minor problems related to the design and maintenance of the HVAC systems which needs modification to achieve improved IAQ. The following strategies are recommended for the correction of such practices:

1. While the study was in progress, the standard 62-1989 was modified to ASHRAE standard 62-1999. The new Standard does not alter the scope or purpose of the previous standard nor its definition of acceptable IAQ. It changed the procedure for calculating space and system ventilation rates to clarify vagaries, correct inaccuracies, strengthen inadequacies, enhance enforceability, and increase design flexibility. It includes minimum ventilation rates both for people-related sources and non-people sources (Stanke, 1999). Hence, any reference should be made to the new standard.

2. The pollutant sources should be identified and controlled in order to improve the IAQ in any building. Smoking has been identified as the major common source of contaminant in commercial and office buildings. Hence, "no smoking policy" should be strictly adopted and implemented, or separate smoking areas need to be created with local exhaust.
3. Outdoor air ventilation rates should be in accordance with the established Standards. CO_2 concentration above 1000 ppm indicates inadequate ventilation. This approach can be effective either when buildings are under-ventilated or where specific contaminant source cannot be identified.
4. Indoor air contaminants can be controlled through ventilation by diluting contaminants with the outdoor fresh air, or by isolating contaminant by providing local exhaust. Local exhaust confines the spread of contaminants by capturing them near the source and exhausting them to the outdoors.
5. Air filtration is the key to proper IAQ. It is done in buildings mainly to prevent contaminant buildup in HVAC equipment and enhance equipment efficiency. Filters of good filtration efficiency should be used.
6. Adequate inspection/maintenance schedule should be adopted for all the HVAC equipment and systems to ensure proper performance. Assign a separate maintenance department for HVAC operation and maintenance.
7. Proper air distribution system and balancing of the air handling system should be ensured. The supply and return air grilles/diffusers should be located in such a way so as to improve air distribution within the space.
8. During the walk-through investigation, it was observed that the return air is through plenum. It should be avoided as it aids in bacterial growth.

9. Provide proper pressurization (positive) of the spaces in order to avoid the infiltration of contaminants from the outside air
10. Provisions should be made in the design of HVAC systems to consider future needs of spaces including its expansion and increase in number of occupants.
11. Regular monitoring of the environmental parameters and CO_2 concentration should be adopted to check for any IAQ problems related to HVAC systems.

6.4 HVAC Design, Operation & Maintenance Guidelines for IAQ

Based upon the literature review, outcome from the analyses of the two questionnaires (HVAC designers and building occupants), walk-through inspection and environmental measurements, general guidelines have been formulated for HVAC system design and operation & maintenance for improved IAQ in hot and humid climatic conditions of the Eastern Province of Saudi Arabia. The specific numbers in the proposed guidelines have been adopted from ASHRAE publication "Principles of HVAC" (Howell, et. al., 1998).

6.4.1 Guidelines for HVAC Systems Design

The following are the general guidelines for HVAC system's designers for improved IAQ in commercial and office buildings in hot and humid climate of Saudi Arabia:

Outside Air Intake

1. Provide unobstructed location of outside air intake louvers.
2. Make sure that the outdoor air quality follows standard criteria.

3. Provide ventilation rate according to ASHRAE standard 62-1999.
4. Do not place exhaust outlets within 7.6 m (25 feet) of the fresh air intake louvers to prevent reintroduction of the exhaust air into the space.
5. Outside intake provisions should be away from road, parking areas. and garbage dumps which could bring in the contaminants.
6. Provide a bird screen of 1/2" minimum spacing to prevent the accumulation of debris in the outside air intake ductworks.
7. Ensure accessibility for cleaning.

Mixing Plenums

1. Ensure that there is no fibrous or moisture absorbing material in direct contact with air.
2. Provide proper floor drain inclination to avoid water accumulation and microbial growth.
3. Ensure accessibility for cleaning.
4. Design negative pressure in mixing plenums to facilitate the entry of outside air.

Filtration

1. Filters should be designed with sufficient efficiency to ensure adequate arrestance and dust spot efficiency. The concentration of particulates suspended in the air shall not exceed 0.05 to 0.07 mg/m^3 which are harmful to human health.
2. Filters should be properly located along the air stream depending on the contaminant source.
3. Ensure complete coverage of air without any bypassing.
4. Use non-moisture absorbing material for filters
5. Recommended air velocity at filter section is 1.5 m/s (300 fpm).
6. Allowable static pressure drop at filter section is 174-199 Pa (0.7 to 0.8 inch of w.g).
7. Ensure easy access to filters for maintenance and replacement.

Cooling Coils / Condensate Pans

1. Ensure that there is no water carryover from cooling coils into the ductwork, which could cause mold growth.
2. Avoid internal insulation of the supply duct upstream of cooling coil, which could degrade over time and promote microbial growth.
3. Air velocity at the cooling coil section should be within 1.5-4 m/s (300-800) fpm.
4. Condensate pan drain should be properly sloped and connected to the sewer system.
5. Ensure accessibility for inspection and maintenance.

Supply Fans

1. Ensure proper fan sizing to provide the required flow rate and overcome the resistance of the ductwork, supply outlets, return intakes, cooling coils, and filters.
2. Draw through fans are recommended for hot humid climates (in blow-through fan configuration, the coils can emit a fog that condenses on the inner edges of the ductwork facilitating mold growth).
3. Ensure accessibility for inspection and maintenance.

Supply Ductworks and Accessories

1. The recommended duct velocities to obtain desired results with minimum noise are as follows: 5-6.6 m/s (1000-1300 fpm) for main ducts, 3-4.6 m/s (600-900 fpm) for branch ducts, and 3-3.6 m/s (600-700 fpm) for branch risers.
2. The allowable static pressure loss for various ductwork components are as follows: 125 Pa (0.50 inch of w.g.) for supply plenum, 12.5 Pa (0.05 inch of w.g.) for supply grille and return plenum, and 100 Pa (0.40 inch of w.g.) for ducted return.
3. Provide proper layout of ductwork for proper air quality delivery, uniform

air distribution, and minimum pressure drop.

4. Ensure air-balancing capability by provision of control over volume dampers.
5. Provide external insulation to ductworks (fiberglass insulation), and avoid using internal insulation that promotes microbial growth.
6. Ensure accessibility for inspection and maintenance.

HVAC Controls

1. Design temperature should be within the range of (as per ASHRAE comfort zone):
   (a) For winter: 21 to 23 °C (70 to 74 °F)
   (b) For summer: 23 to 26 °C (74 to 78 °F)
2. Design relative humidity should be within the range of (as per ASHRAE comfort zone):
   (a) For winter: 20-30% RH
   (b) For summer: 50-60% RH
3. Air movement should be within the range of 0.127 to 0.229 m/s (25 to 45 fpm).
4. Provide air circulation of 4-10 air changes per hour.
5. Properly locate the thermostat, as poor location will result in discomfort to the occupants.
6. Noise levels should not exceed 40-45 NC (maximum).

Exhaust Fans

1. Provide exhaust systems to all toilets, kitchens and other contaminant generating areas.
2. Provide sufficient makeup air to compensate for the exhaust air.
3. Exhaust areas should be slightly negatively pressurized as compared to rest of the building so as to prevent infiltration of odor to occupied spaces.
4. Garage/parking areas within the building should be designed at slightly negative pressure relative to the building so as to prevent infiltration of

contaminants to occupied spaces.

5. Provide 100 percent exhaust for smoking lounges.
6. Ensure accessibility for inspection and maintenance.

Mechanical Room

1. Properly locate the mechanical room in the building.
2. Provide unobstructed access to all components for inspection and maintenance.

6.4.2 Guidelines for HVAC Systems Operation and Maintenance

The following are the general guidelines for the operation and maintenance of HVAC systems for improved IAQ in commercial and office buildings in hot and humid climate of Saudi Arabia:

Outside Air Intake

1. Ensure that the outside air louvers and bird screens are unobstructed.
2. Make sure that the outside air dampers are operational and balanced.
3. Ensure that the outside air damper seals completely when closed.
4. Standing water or bird droppings should not be present in the vicinity of outside air intake louvers.
5. Ensure that no contaminants or odors enter through outside air intake.
6. Regularly clean air louvers and bird screens.

Mixing Plenums

1. The outside air dampers, return air dampers, and exhaust air dampers should be balanced to ensure proper proportional mixing.
2. Make sure that all damper motors are operational.
3. Ensure that the floor drain is trapped properly and there is no standing water.
4. Ensure that the mixing plenum is free from corrosion.

5. Mixing plenum should be maintained in clean condition.

Filtration

1. Ensure correct pressure drop across the filter as per manufacturer's recommendation.
2. Ensure that the filters are accessible to inspect and clean.
3. Inspect frequently for any signs of blockage / microbial growth (moisture absorbing filters could be the breeding places for mold in humid climates).
4. Clean and replace on a regular basis.
5. Inspect filter type and size to ensure complete coverage without bypassing.

Cooling Coils / Condensate Pans

1. Inspect for any signs of condensation problems.
2. Ensure that the cooling coils / condensate pans are maintained, and accessible to inspect and clean.
3. Make sure that there is no water accumulation or microbial growth in condensate pans.
4. Ensure that the cooling coils are free from scaling / corrosion.

Supply Air Fans

1. Ensure that the supply air fans are accessible to inspect and clean.
2. Clean fan blades for dust / dirt accumulation.
3. Provide proper belt tension.
4. Keep vibrations at minimum level.
5. Inspect for any signs of corrosion and ensure proper painting of fans (the hot-humid environment is likely to corrode the surface of supply fans).

Supply Ductworks and Accessories

1. Clean at least once in two years.
2. Inspect for any leakages / air-tightness from ductworks.
3. Ensure that volume control dampers are operational and balanced.

4. Make sure that all the access doors in ducts are closed to prevent any undesired entry.
5. Balance within 3-5 years or after renovations.
6. Ensure proper air-distribution to all the space (stagnant air could result due to low airflow rates or poor air distribution).
7. Inspect grilles / diffusers for any signs of corrosion.
8. Clean grilles / diffuser on a regular basis.

HVAC Controls

1. Ensure proper temperature and humidity settings for winter and summer (Improper temperature/humidity control can result in discomfort and perception of poor IAQ, and may encourage indoor mold growth).
2. Monitor the actual space temperature and humidity, and compare with the standards.
3. Check occupant satisfaction with indoor environment.
4. Adjust temperature and humidity settings if warranted.
5. Ensure that all the HVAC controls are in proper working conditions.

Pollutant Pathways

1. Stairwells should close and latch without any opening for uncontrolled airflow.
2. Ensure unobstructed return air path.
3. Ducted returns should be balanced every 3-5 years or after renovation.

Exhaust Fans

1. Ensure that all exhaust fans are operational.
2. Provide unobstructed sufficient makeup air to compensate for exhaust air.
3. Doors to building should close tightly to prevent any infiltration of contaminated air. Make sure that the smoking lounges have 100 percent exhaust.
4. Ensure that the toilets, kitchens and parking areas have negative pressure

relative to the building.

5. Eliminate smoking or isolate smoke source in terms of time and space by assigning separate smoking area.

Mechanical Room

1. Ensure that the equipment is in overall good condition.
2. Make sure that all the controls are operational and calibrated.
3. Control drawings should be posted.
4. Ensure that the sump of cooling tower is clean and there are no signs of slime / algae / bacterial growth.
5. Biocide treatment and dirt separator are working for cooling tower.
6. Inspect for any leaks of refrigerant in chillers.
7. Avoid storing any material in the mechanical room and ensure unobstructed access to the equipment.

6.5 Checklists

Based upon the proposed guidelines, two separate checklists have been formulated that can be used by HVAC Designers, and HVAC Operation & Maintenance personnel to check their compliance with suggested guidelines for better IAQ. The user needs to check the appropriate "Yes" or "No" answer for each question in Table 6.1 and 6.2. A tick (✓) may be marked in the suitable box. However, the correct answer boxes are shaded for the convenience of users.

6.5.1 HVAC Design Checklist for IAQ

Table 6.1: HVAC Design Checklist for IAQ

Outside Air Intake		Yes	No	Comments
1	Unobstructed location of outside air intake louvers?			
2	Outdoor air quality follows standard criteria?			
3	Ventilation rate according to ASHRAE standard 62-1999?			
4	Exhaust outlet within 7.6 m (25 feet) of the fresh air intake louvers?			
5	Are outside air intake provisions away from road/parking areas/garbage dumps?			
6	Bird screen of 1/2" minimum spacing at the air intake ductworks?			
7	Accessibility for cleaning?			

Mixing Plenums		Yes	No	Comments
1	Any fibrous or moisture absorbing material in direct contact with air?			
2	Proper floor drain inclination?			
3	Accessibility for cleaning?			
4	Negative pressure in mixing plenums?			

Filtration		Yes	No	Comments
1	Are filters designed with sufficient efficiency to ensure adequate arrestance?			
2	Are filters properly located along the air stream depending on contaminant source?			
3	Is there a complete coverage of air without any bypassing?			
4	Moisture absorbing material used for filters?			
5	Air velocity at filter section is 1.5 m/s (300 fpm)?			
6	Static pressure drop at filter section is 0.7 to 0.8 inch of w.g.?			
7	Easy access to filters for maintenance and replacement?			

Cooling Coils / Condensate Pans		Yes	No	Comments
1	Is it ensured that there is no water carryover from cooling coils into the ductwork?			
2	Are the supply air ducts internally insulated?			
3	Air velocity at the cooling coil section is 1.5-4 m/s (300-800 fpm)?			
4	Is the condensate pan drain properly sloped and connected to the sewer system?			
5	Accessibility for inspection and maintenance?			

Table 6.1: HVAC Design Checklist for IAQ (cont.)

Supply Air Fans		Yes	No	Comments
1	Are the fans properly sized to overcome the resistance of ductwork, supply outlets, return intakes, cooling coils, and filters?			
2	Are the fans draw-through type?			
3	Accessibility for inspection and maintenance?			

Supply Ductworks and Accessories		Yes	No	Comments
1	Are the duct velocities as follows: 5-6.6 m/s (1000-1300 fpm) for main ducts, 3-4.6 m/s (600-900 fpm) for branch ducts, and 3-3.6 m/s (600-700 fpm) for branch risers?			
2	Is the static pressure loss for various ductwork components are as follows: 125 Pa (0.50 inch of w.g.) for supply plenum, 12.5 Pa (0.05 inch of w.g.) for supply grille and return plenum, and 100 Pa (0.40 inch of w.g.) for ducted return?			
3	Is there a proper layout of ductwork for proper air quality delivery, uniform air distribution, and minimum pressure drop?			
4	Is there a provision to control volume dampers for air-balancing?			
5	Are the ducts externally insulated?			
6	Accessibility for inspection and maintenance?			

HVAC Controls		Yes	No	Comments
1	Is the design temperature within the range of (a) 21 to 23 deg.C (70 to 74 deg.F) for winter (b) 23 to 26 deg.C (74 to 78 deg.F) for summer?			
2	Is the design relative humidity within the range of (a) 20-30% for winter (b) 50-60% for summer?			
3	Is the air movement within the range of 0.127 to 0.229 m/s (25 to 45 fpm)?			
4	Is the air circulation within the range of 4-10 air changes per hour?			
5	Are the thermostats properly located?			
6	Does the noise levels exceed 40-45 NC (maximum)?			

Table 6.1: HVAC Design Checklist for IAQ (cont.)

Exhaust Fans		Yes	No	Comments
1	Are the exhaust systems provided to all toilets, kitchens and other contaminant generating areas?			
2	Is there sufficient makeup air provided to compensate for the exhaust air?			
3	Are the exhaust areas slightly negatively pressurized to rest of the building?			
4	Are the garage/parking areas within the building designed at slightly negative pressure relative to the building?			
5	Are the smoking lounges provided with 100 percent exhaust?			
6	Accessibility for inspection and maintenance?			

Mechanical Room		Yes	No	Comments
1	Are the mechanical rooms properly located in the building?			
2	Is there an unobstructed access to all components for inspection and maintenance?			

6.5.2 HVAC Operation and Maintenance Checklist for IAQ

Table 6.2: HVAC Operation and Maintenance Checklist for IAQ

Outside Air Intake		Yes	No	Comments
1	Are the outside air louvers and bird screens unobstructed?			
2	Are the outside air dampers operational and balanced?			
3	Does the outside air damper seals completely when closed?			
4	Is there standing water or bird droppings within the vicinity of outside air intake louvers?			
5	Are there any contaminants or odors that enter through outside air intake?			
6	Are the air louvers and bird screens regularly cleaned?			

Table 6.2: HVAC Operation and Maintenance Checklist for IAQ (cont.)

Mixing Plenums		Yes	No	Comments
1	Are the outside air dampers, return air dampers, and exhaust air dampers balanced to ensure proper proportional mixing?			
2	Are all damper motors operational?			
3	Is the floor drain trapped properly without any standing water?			
4	Is the mixing plenum free from corrosion?			
5	Is the mixing plenum maintained in clean condition?			

Filtration		Yes	No	Comments
1	Is pressure drop across the filter as per manufacturer's recommendation?			
2	Are the filters accessible to inspect and clean?			
3	Is there a regular inspection for any signs of blockage / microbial growth?			
4	Are the filters cleaned and replaced on a regular basis?			
5	Are the filters inspected for their type and size to ensure complete coverage without bypassing?			

Cooling Coils / Condensate Pans		Yes	No	Comments
1	Are there any signs of condensation problems?			
2	Are the cooling coils / condensate pans maintained, and accessible to inspect and clean?			
3	Is there any water accumulation or microbial growth in condensate pans?			
4	Are the cooling coils free from scaling / corrosion?			

Supply Air Fans		Yes	No	Comments
1	Are the supply air fans accessible to inspect and clean?			
2	Are the fan blades cleaned for dust / dirt accumulation?			
3	Are the fan belts provided with proper tension?			
4	Are the vibrations maintained at minimum level?			
5	Are the fans inspected for any signs of corrosion and their proper painting is ensured?			

Table 6.2: HVAC Operation and Maintenance Checklist for IAQ (cont.)

	Supply Ductworks and Accessories	Yes	No	Comments
1	Are the ductworks cleaned at least once in two years?			
2	Are there for any leakages in the ductworks?			
3	Are the volume control dampers operational and balanced?			
4	Are all the access doors in ducts closed to prevent any undesired entry?			
5	Are the ductworks balanced within 3-5 years or after renovations?			
6	Is there a uniform air-distribution to all the space?			
7	Are there any signs of corrosion in grilles / diffusers?			
8	Are the grilles / diffusers cleaned on a regular basis?			

	HVAC Controls	Yes	No	Comments
1	Is there a proper temperature and humidity setting for winter and summer?			
2	Are the actual space temperature and humidity recorded and then compared with the standards?			
3	Are the space occupants satisfied with indoor environment?			
4	Are the temperature and humidity settings adjusted if warranted?			
5	Are all the HVAC controls in proper working condition?			

	Pollutant Pathways	Yes	No	Comments
1	Do the stairwells close and latch without any opening for uncontrolled airflow?			
2	Is the return air path unobstructed?			
3	Are the ducted returns balanced every 3-5 years or after renovation?			

	Exhaust Fans	Yes	No	Comments
1	Are all exhaust fans are operational?			
2	Is there an unobstructed sufficient makeup air to compensate for exhaust air?			
3	Do the doors to building close tightly to prevent any infiltration of contaminated air?			
4	Do the toilets, kitchens and parking areas have negative pressure relative to the building?			
5	Is there any provision to eliminate smoking or isolate smoke source in terms of time and space by assigning separate smoking area?			
6	Are the smoking lounges provided with 100 percent exhaust?			

Table 6.2: HVAC Operation and Maintenance Checklist for IAQ (cont.)

Mechanical Room		Yes	No	Comments
1	Is the equipment in overall good condition?			
2	Are all the controls operational and calibrated?			
3	Are the control drawings posted?			
4	Is the sump of cooling tower clean and there are no signs of slime / algae / bacterial growth?			
5	Are the biocide treatment and dirt separator working for cooling tower?			
6	Are there any leaks of refrigerant in chillers?			
7	Is there any material storage in the mechanical room that may obstruct easy access to the equipment?			

6.6 Future Research

This research was directed towards the investigation of the impact of HVAC systems on IAQ in commercial and office buildings in the Eastern Province of Saudi Arabia. It is recommended that researchers select one type of HVAC system and study its behavior for IAQ in only one type of building, for example office buildings. More elaborate measurements should be carried out for longer duration for major suspected pollutants.

Another possibility of future research in this area is to conduct thorough investigation of one huge building as a case study, which could be a high rise building or a huge shopping mall, to determine how this building have been designed and operated, and the possible scopes for improvement. The impact of VAV systems on IAQ could also be studied in detail in the hot-humid climate of Saudi Arabia.

APPENDICES

Appendix A

Information Request

بسم الله الرحمن الرحيم

Ministry of Higher Education
King Fahd University of Petroleum & Minerals
COLLEGE OF ENVIRONMENTAL DESIGN
ARCHITECTURAL ENGINEERING DEPARTMENT

وزارة التعليم العالي
جامعة الملك فهد للبترول والمعادن
كلية تصاميم البيئة
قسم الهندسة المعمارية

March 16, 1999.

Dear Sir,

The Architectural Engineering Department at the King Fahd University of Petroleum & Minerals is presently engaged in a study of ***the evaluation of Heating, Ventilating and Air-conditioning (HVAC) systems pertaining to Indoor Air Quality (IAQ) in commercial buildings in the Eastern Province of Saudi Arabia.***

The purpose of this study is to evaluate the indoor spaces in commercial buildings and to assess the impact of air-conditioning systems on these spaces. The ultimate objective of the study is to suggest means to improve the indoor air quality in commercial buildings.

We request you to kindly participate by providing the needed information related to the subject matter of the study. We ensure you that the information will be held in strict confidence and used for research purposes only. We strongly believe that your contribution is important for the successful completion of the study.

Your active participation will be highly appreciated.

Should you have any queries regarding the study, please feel free to contact the undersigned.

Dr. Ismail M. Budaiwi
Research Advisor.
Phone: 860 3279
Fax: 860 3785

Raza Ahmed Khan
Research Assistant.
Phone: 860 3275
860 6186

كلية تصاميم البيئة
الهندسة المعمارية
COLLEGE OF ENV. DESIGN
ARCHITECTURAL ENGINEERING

Appendix B

HVAC Designer's Questionnaire

Design Questionnaire

on

Indoor Air Quality

For details or information, please contact

Dr. Ismail Budaiwi
(860 3279)

Raza Ahmed Khan
(860 3275)

Architectural Engineering Department
King Fahd University of Petroleum & Minerals
Dhahran, Saudi Arabia.

Firm name: ____________________

Date and time: ____________________ Serial Number: __________

1. **How long have you been involved in designing the HVAC systems in buildings?**
   - ☐ Less than 2 years
   - ☐ 2-5 years
   - ☐ 5-10 years
   - ☐ 10-15 years
   - ☐ More then 15 years

2. **What kind of buildings does your organization deals mostly?**
   - ☐ Residential
   - ☐ Commercial & Office
   - ☐ Industrial
   - ☐ Institutional
   - ☐ Others (specify) ____________________

3. **What type of HVAC system is used in commercial & office buildings in Saudi Arabia?**

	Never	Seldom	Sometimes	Often
☐ VAV systems	___	___	___	___
☐ Packaged Rooftop units	___	___	___	___
☐ Split Systems	___	___	___	___
☐ Constant Volume Systems	___	___	___	___
☐ Others (specify)__________	___	___	___	___

Please add details (if any):

4. **Who is the manufacturer of these HVAC systems in commercial & office buildings?**

	Never	Seldom	Sometimes	Often
☐ Carrier	___	___	___	___
☐ Trane	___	___	___	___
☐ York	___	___	___	___
☐ Zamil	___	___	___	___
☐ Others (specify)__________	___	___	___	___

5. **The criteria for selection of the manufacturer is**
   - ☐ Specified by owner
   - ☐ Suitable for weather conditions of Saudi Arabia
   - ☐ Availability in the market
   - ☐ Good experience with the product
   - ☐ Others (specify) ____________________

6. **What are the criteria for designing and selecting the HVAC systems?**
   - ☐ Energy conservation
   - ☐ Thermal comfort
   - ☐ Indoor air quality
   - ☐ Others (specify) ____________________

7. **What is the range of indoor temperature that you normally design for comm. & office buildings?**
   - ☐ 20°-22°C
   - ☐ 22°-24°C
   - ☐ 24°-26°C
   - ☐ Others (specify) ____________________

8. **What is the range of relative humidity that you design for commercial & office buildings?**
   - ☐ 40 – 45 %
   - ☐ 45 – 50 %
   - ☐ 50 – 55 %
   - ☐ 55 – 60 %
   - ☐ Others (specify) ____________________

9. What is the ventilation rate (outside air) that you incorporate to design the HVAC system for commercial & office buildings?
   - ❑ 5 – 10 cfm per person
   - ❑ 10 – 15 cfm per person
   - ❑ 15 – 20 cfm per person
   - ❑ Others (specify) ________________

10. What kind of filters do you generally recommend?
    - ❑ Media filters
    - ❑ High efficiency particulate air filter (HEPA)
    - ❑ Electrostatic air cleaners (EAC)
    - ❑ Others (specify) ________________

11. What is the air filtration efficiency that you normally specify?
    - ❑ More than 90%
    - ❑ 70 – 80 %
    - ❑ 60 – 70 %
    - ❑ 50 – 60 %
    - ❑ Others (specify) ________________

12. Do you consider the maintenance accessibility to the HVAC equipment?
    - ❑ Yes
    - ❑ No

13. Do you take any measure during the design of coil condensation pan to ensure complete condensate drain and prevent blockage?
    - ❑ Yes
    - ❑ No

14. What kind of thermal insulation you specify for the ducting system?
    - ❑ Fiberglass
    - ❑ Cellulose fiber
    - ❑ Rock/slag wool
    - ❑ Others (specify) ________________

15. The location of duct insulation that you prefer is
    - ❑ Internal to the duct
    - ❑ External to the duct

16. Do you allocate separate areas for smoking with local exhaust?
    - ❑ Yes
    - ❑ No

17. Do you provide local exhaust system for spaces with localized contaminant generation (like kitchen, chemical lab, etc.) in commercial & office buildings?
    - ❑ Yes
    - ❑ No

18. What are the considerations you make while designing for fresh air intake?
    - ❑ Outdoor air quality
    - ❑ Location of air intake
    - ❑ Bird screens and mesh
    - ❑ Others (specify) ________________

19. Do you consider air distribution pattern in spaces when selecting and locating supply and return air grilles?
    - ❑ Yes
    - ❑ No

Thank you. We appreciate your co-operation in carrying out this study.

Appendix C

Building Occupant's Questionnaire

Research Questionnaire

on

Indoor Air Quality

For details or information, please contact

Dr. Ismail Budaiwi
(860 3279)

Raza Ahmed Khan
(860 3275)

Architectural Engineering Department
King Fahd University of Petroleum & Minerals
Dhahran, Saudi Arabia.

Building name:____
Date and time:_______________________ Serial Number: __________

GENERAL INFORMATION

1. **Age**
   - ❑ 20-30 years
   - ❑ 31-40 years
   - ❑ 41-50 years
   - ❑ 51-60 years
   - ❑ above 60 years

2. **Occupation**
   - ❑ Salesman
   - ❑ Technician
   - ❑ Businessman
   - ❑ Engineer
   - ❑ Others (specify) ________________

3. **Duration of stay per day in this space**
   - ❑ less that 2 hours
   - ❑ 2-4 hours
   - ❑ 4-6 hours
   - ❑ 6-8 hours
   - ❑ more than 8 hours

4. **Period of occupation of the space**
   - ❑ less than 3 months
   - ❑ 3-6 months
   - ❑ 6-12 months
   - ❑ more than 12 months

SYMPTOMS

5. **What symptoms have you experienced working in this environment?**

	Never	Seldom	Sometimes	Often
❑ Headaches	___	___	___	___
❑ Eye irritation	___	___	___	___
❑ Nose irritation	___	___	___	___
❑ Throat irritation	___	___	___	___
❑ Dry mouth	___	___	___	___
❑ Breathing shortness	___	___	___	___
❑ Chest pains	___	___	___	___
❑ Fatigue	___	___	___	___
❑ Fever	___	___	___	___
❑ Skin rash	___	___	___	___
❑ Drowsiness	___	___	___	___

6. **Do these symptoms go away upon leaving this space?**
   - ❑ Yes
   - ❑ No

7. **How often do these symptoms occur?**
   - ❑ Daily
   - ❑ Weekly
   - ❑ Twice a week
   - ❑ Once a month

8. **Do these symptoms occur during a particular part of the year? Or time of the day?**
   - ❑ Summer
   - ❑ Winter
   - ❑ Morning
   - ❑ Evening

9. **How long do these symptoms last?**
- ❑ During morning hours
- ❑ During afternoon hours
- ❑ All day
- ❑ All the time

10. **Do you suffer from any medical problems that may be related to these symptoms like**
- ❑ Asthma
- ❑ Allergies
- ❑ Hay fever
- ❑ Migraines
- ❑ Others (specify) ____________________

11. **The work area is**
- ❑ Unbearable
- ❑ Uncomfortable
- ❑ Comfortable

12. **How do you feel when you leave this space**
- ❑ Better
- ❑ Same as before
- ❑ Worse

13. **How would you describe your work environment? (too hot, cold, odor, dusty, humid, etc.)**

WORK PLACE ENVIRONMENT

14. **The temperature in this space is**
- ❑ Cold
- ❑ Slightly Cool
- ❑ Comfortable
- ❑ Slightly Warm
- ❑ Hot

15. **The humidity in this space is**
- ❑ Too dry
- ❑ Dry
- ❑ Comfortable
- ❑ Humid
- ❑ Too humid

16. **The noise level in this space is**
- ❑ Too noisy
- ❑ Noisy
- ❑ Quite

17. **The lighting level in this space is**
- ❑ Low (dim)
- ❑ Satisfactory (comfortable)
- ❑ Intense (glare)

18. **The air in this space in terms of cleanliness is**
- ❑ Dirty
- ❑ Smoky
- ❑ Clean

19. **The movement of air in this space is**
- ☐ Still
- ☐ Moderate
- ☐ Drafty

20. **HVAC systems (Air-conditioners) are used in this space for**
- ☐ 6 months (April to September)
- ☐ 9 months (February to October)
- ☐ 12 months (All year-round)

21. **Do you have any complaint about your HVAC system?**
- ☐ Too noisy
- ☐ Bad smell
- ☐ Too hot or cold
- ☐ Too much air
- ☐ Others (specify) ____________________

22. **How frequently does your HVAC system needs maintenance?**
- ☐ Every 6 months
- ☐ Every 9 months
- ☐ Yearly
- ☐ Once in 2 years

23. **The presence of odor in this space is**
- ☐ None
- ☐ Slight
- ☐ Moderate
- ☐ Strong

24. **The odor in this space is probably due to**
- ☐ Cigarette
- ☐ Car exhaust
- ☐ Carpet
- ☐ Toilet
- ☐ Furniture
- ☐ Others (specify) ____________________

25. **Do you smoke?**
- ☐ Yes
- ☐ No

26. **Are you bothered by others smoking in your work area?**
- ☐ Yes
- ☐ No

27. **How often do you need to clean the office furniture for dust accumulation?**
- ☐ Twice daily
- ☐ Once daily
- ☐ Once in two days
- ☐ Twice a week
- ☐ Once in a week

Thank you. We appreciate your co-operation in carrying out this study.

اســــتبيان لبـــــــحث

عن

جودة الهواء داخل المبانـي

لمزيد من المعلومات المرجو الاتصال بـــ
د. إسماعيل بن محمد بديوي
(٨٦٠٣٢٧٩)

أو الباحث رضا أحمد خان
(٨٦٠٣٢٧٥)

قسم الهندسة المعمارية
جامعة الملك فهد للبترول والمعادن
الظهران- المملكة العربية السعودية

أسم المبنى : ______________________________

التاريخ والوقت : ______________________________

رقم التسلسل ________

معلومات عامة

١- العمر

☐ ٢٠ – ٣٠ سنة ☐ ٣١ – ٤٠ سنة ☐ ٤١ – ٥٠ سنة

☐ ٥١ – ٦٠ سنة ☐ فوق ٦٠ سنة

٢- الوظيفة

☐ بائع ☐ فني ☐ رجل أعمال ☐ مهندس ☐ أخرى

٣- الوقت الذي تقضيه في هذا المكان

☐ أقل من ساعتين
☐ ٢ – ٤ ساعات
☐ ٤ – ٦ ساعات
☐ ٦ – ٨ ساعات
☐ أكثر من ٨ ساعات

٤- منذ متى تقيم في هذا المكان

☐ أقل من ٣ شهور
☐ ٣ – ٦ شهور
☐ ٦ – ١٢ شهور
☐ أكثر من ١٢ شهر

الأعراض

٥- ما هي الأعراض التي تصيبك عند العمل بهذا المكان ؟

	قطعياً	نادراً	أحياناً	دائماً
☐ صداع	___	___	___	___
☐ حكة العين	___	___	___	___
☐ حكة الأذن	___	___	___	___
☐ حكة الأنف	___	___	___	___
☐ حكة الحنجرة	___	___	___	___
☐ جفاف الفم	___	___	___	___
☐ ضيق النفس	٧ ___	___	___	___
☐ آلام الصدر	___	___	___	___
☐ الإنهاك	___	___	___	___
☐ ارتفاع درج الحرارة	___	___	___	___
☐ احمرار الجلد	___	___	___	___
☐ الدوخة	___	___	___	___

٦- هل تزول هذه الأعراض بالخروج من المبنى ؟

☐ نعم ☐ لا

٧- متى تشعر بهذه الأعراض عادةً ؟

☐ يومياً ☐ أسبوعياً ☐ مرتين أسبوعياً ☐ مرة في الشهر

٨- هل تحدث هذه الأعراض في موسم معيّن من السنة ؟ أو وقت معيّن من اليوم ؟

☐ صيف شتاء

☐ صباح مساء

٩- كم من الوقت تتم هذه الأعراض

- ☐ ساعات الصباح
- ☐ ساعات بعد الظهر
- ☐ طوال اليوم
- ☐ طول الوقت

١٠- هل تشكو من أي مرض له علاقة بهذه الأعراض ؟

- ☐ ربو
- ☐ حساسية
- ☐ ارتفاع درجة الحرارة
- ☐ أخرى (صداع)

١١- منطقة العمل

- ☐ سيئة للغاية
- ☐ غير مريحة
- ☐ مريحة

١٢- بماذا تشعر عند مغادرة هذا المكان ؟

- ☐ أحسن
- ☐ لا تتغير
- ☐ أسوء

١٣- كيف تصف الجو في مكان العمل ؟

☐ حار جداً ☐ بارد ☐ ملوث ☐ رطب ☐ آخر

مكان العمل

١٤- درجة حرارة المكان

- ☐ بارد
- ☐ بارد نسبياً
- ☐ مريح
- ☐ دافئ نسبياً
- ☐ حار

١٥- الرطوبة في هذا المكان ؟

☐ حار جداً ☐ جاف ☐ مريح ☐ رطب ☐ رطب جداً

١٦- مستوى الضجيج في هذا المكان

- ☐ مزعج جداً
- ☐ مزعج
- ☐ هادئ

١٧- مستوى الإضاءة في هذا المكان

☐ ضعيف ☐ ملائم ☐ مجهد

١٨- نقاوة الهواء في هذا المكان

- ☐ وسخ
- ☐ مليئ بالدخان
- ☐ نظيف

١٩-حركة الهواء في المكان

☐ ثابت ☐ وسط ☐ قوية

٢٠- المكيف في هذا المبنى يستخدم

☐ ٦ شهور (أبريل - سبتمبر)

☐ ٩ شهور (فبراير - أكتوبر)

☐ ١٢ شهر

٢١- هل لديك شكوى من أي جهات التكييف ؟.

☐ مزعج جداً

☐ رائحة سيئة

☐ حار جداً أو بارد

☐ الهواء كثير جداً

☐ أخرى (حدد)

٢٢- كم درجة العطل في التكييف ؟.

☐ كل ٦ شهور

☐ كل ٩ شهور

☐ كل سنه

☐ مرّة كل سنتين

٢٣- وجود الرائحة في المكان

☐ لا توجد

☐ نادراً

☐ قليلة

☐ كثيرة

٢٤- يوجد رائحة في هذا المكان بسبب

☐ التدخين

☐ عادم السيارات

☐ الموكيت

☐ الحمام

☐ المفروشات

☐ أخرى (حدد)

٢٥- هل أنت مدخن

☐ نعم ☐ لا

٢٦- هل تختلط بالمدخنين في مكان العمل

☐ نعم ☐ لا

٢٧- كم مرة تحتاج للتنظيف من آثار الغبار؟.

☐ مرتين يومياً ☐ مرة يومياً ☐ مرة كل يومين

☐ مرتين بالأسبوع ☐ مرة بالأسبوع ☐

شكراً جزيلاً نحن نقدر لكم تعاونكم في إنجاز هذه الدراسة

Appendix D

Building Assessment Form

Building Assessment Form

Building: ________________________ Type: Commercial / Office
Zone: ______________ Floors: ______________ Location: ______________
Year of construction: ______________ Working hours: ______________

HVAC system type: ______________ Manufacturer: ______________
Model No: ______________ Year of installation: ______________

Date: ______________ Day: ______________ Time: ______________

SPACE CONDITION	Area (approximately)	=
	Number of occupants	=
	Noticeable odor	= none / moderate / strong
	Temperature	= cold / cool / comfortable / warm / hot
	Humidity	= dry / comfortable / humid
	Lighting level	= low / satisfactory / high
	Vibration and noise level	= low / satisfactory / high
	Dirt (traces of dust)	= yes / no
	Smoking	= yes / no
	Noticeable flow of air (draught)	= yes / no
	Dampness (wetness / moisture)	= yes / no
DUCTWORK	Proper layout for air distribution	= yes / no
	Return air plenum	= yes / no
	Duct lining	= inside / outside
	Microbial growth in ductworks	= yes / no
	Access doors available	= yes / no
COOLING COIL	Drain pans trapped properly	= yes / no
	Condensation problem	= yes / no
	Evidence of water leakage	= yes / no
	Microbial growth in condensate pans	= yes / no
	Corrosion problem	= yes / no
	Inspection access available	= yes / no
FILTER	Filter type	= media / HEPA / electrostatic
	Condition of filter	= excellent / good / bad / worst
	Moisture buildup	= yes / no
	Filter location	= before coil / after coil
	Frequency of cleaning	=
	Inspection access available	= yes / no
INTAKE	Fresh air intake	= yes / no
	Bird screen obstructed	= yes / no
	Parking facility or road nearby	= yes / no
	Exhaust outlet within 25 feet	= yes / no
GENERAL	Central exhaust system	= yes / no
	Separate smoking areas with exhaust	= yes / no
	Doors to building close tightly	= yes / no
	Mechanical room conditions	= excellent / good / bad / worst
	Controls are operational	= yes / no
	Maintenance/inspection schedule	= yes / no
	Contaminant generation areas	= yes / no

Appendix E

Space Evaluation Form

Evaluation Form

Building: ______________________________ Type: Commercial / Office
Floors: ________________________ Location: ______________________
Year of construction: ______________ Working hours: ______________________

HVAC system type: __________________ Manufacturer: __________________
Model No: _______________________ Year of installation: __________________

Date: _____________________________ Day: ___________________________

Set-point temperature (°C):

Time: ______________

Morning

	Outdoor Air	Supply Air	Room Air	Return Air
emperature (°C)				
elative Humidity (%)				
O_2 concentration (ppm)				

Time: ______________

Afternoon

	Outdoor Air	Supply Air	Room Air	Return Air
emperature (°C)				
elative Humidity (%)				
O_2 concentration (ppm)				

Time: ______________

Evening

	Outdoor Air	Supply Air	Room Air	Return Air
emperature (°C)				
elative Humidity (%)				
O_2 concentration (ppm)				

Comments of Operation & Maintenance personnel:

Remarks:

Appendix F

HVAC Designer's Questionnaire Data

Questions to HVAC Designers	Percentage (%)	[redacted]	[redacted]
[redacted]			
Less than 2 years	0		
2-5 years	16		
5-10 years	31		
10-15 years	19		
More than 15 years	34		
[redacted]			
Residential	69		
Commercial & Office	91		
Industrial	78		
Institutional	34		
Others	9		
[redacted]			
VAV systems	13	41	31
Packaged Rooftop units	0	31	66
Split Systems	3	25	63
Constant Volume All-Air Systems	16	50	28
Others	0	0	0
[redacted]			
Carrier	3	22	69
Trane	3	28	63
York	6	38	28
Zamil	0	28	66
Others	0	9	6
[redacted]			
Specified by owner	41		
Suitable for weather conditions	69		
Availability in the market	53		
Good experience with the product	69		
Others	16		
[redacted]			
Energy conservation	59		
Thermal comfort	81		
Indoor air quality	75		
Others	3		
[redacted]			
20-22 deg.C	3		
22-24 deg.C	69		
24-26 deg.C	28		
Others	0		
[redacted]			
40 – 45 %	3		
45 – 50 %	19		
50 – 55 %	78		
55 – 60 %	0		
Others	0		

Questions to HVAC Designers	Percentage (%)
[illegible]	
5 – 10 cfm/person	9
10 – 15 cfm/person	34
15 – 20 cfm/person	51
Others	6
[illegible]	
Media filters	75
High efficy. particulate air filter	41
Electrostatic air cleaners	6
Others	22
[illegible]	
More than 90%	31
70 – 80 %	50
60 – 70 %	13
50 – 60 %	3
Others	16
[illegible]	
Yes	100
No	0
[illegible]	
Yes	81
No	19
[illegible]	
Fiberglass	100
Cellulose fiber	0
Rock/slag wool	3
Others	3
[illegible]	
Internal to the duct	3
External to the duct	100
[illegible]	
Yes	53
No	47
[illegible]	
Yes	100
No	0
[illegible]	
Outdoor air quality	44
Location of air intake	84
Bird screens & mesh	66
Others	16
[illegible]	
Yes	100
No	0

Appendix G

Building Occupant's Questionnaire Data

Questions to Building Occupants	[illegible]	Percentage (%)	[illegible]	Percentage (%)	[illegible]	Percentage (%)	[illegible]	Percentage (%)
[illegible]								
20-30 years	[illegible]	40.77	[illegible]	33.33	[illegible]	53.19		42.66
31-40 years	[illegible]	37.69	[illegible]	38.71	[illegible]	36.70		37.70
41-50 years	[illegible]	19.23	[illegible]	15.05	[illegible]	8.51		13.69
51-60 years	[illegible]	1.54	[illegible]	12.37	[illegible]	1.60		5.56
above 60 years	[illegible]	0.77	[illegible]	0.54	[illegible]	0.00		0.40
[illegible]								
Salesman	[illegible]	4.62	[illegible]	7.53	[illegible]	80.32		33.93
Technician	[illegible]	7.69	[illegible]	6.99	[illegible]	3.72		5.95
Businessman	[illegible]	0.00	[illegible]	2.15	[illegible]	6.91		3.37
Engineer	[illegible]	22.31	[illegible]	49.46	[illegible]	0.53		24.21
Others	[illegible]	65.38	[illegible]	33.87	[illegible]	7.98		32.34
[illegible]								
less that 2 hours	[illegible]	0.77	[illegible]	0.00	[illegible]	1.60		0.79
2-4 hours	[illegible]	1.54	[illegible]	0.00	[illegible]	0.00		0.40
4-6 hours	[illegible]	3.85	[illegible]	4.30	[illegible]	5.32		4.56
6-8 hours	[illegible]	46.15	[illegible]	19.89	[illegible]	27.13		29.37
more than 8 hours	[illegible]	47.69	[illegible]	75.81	[illegible]	67.02		65.28
[illegible]								
less than 3 months	[illegible]	4.62	[illegible]	9.14	[illegible]	4.26		6.15
3-6 months	[illegible]	8.46	[illegible]	4.30	[illegible]	6.38		6.15
6-12 months	[illegible]	11.54	[illegible]	26.34	[illegible]	15.96		18.65
more than 12 months	[illegible]	74.62	[illegible]	60.22	[illegible]	73.94		69.05
[illegible]								
Headaches	[illegible]	46.92	[illegible]	40.86	[illegible]	50.53		46.03
Eye irritation	[illegible]	23.08	[illegible]	27.96	[illegible]	29.79		27.38
Nose irritation	[illegible]	25.38	[illegible]	26.88	[illegible]	30.85		27.98
Throat irritation	[illegible]	26.92	[illegible]	30.11	[illegible]	25.53		27.58
Dry mouth	[illegible]	35.38	[illegible]	21.51	[illegible]	19.15		24.21
Breathing shortness	[illegible]	6.92	[illegible]	16.13	[illegible]	10.64		11.71
Chest pains	[illegible]	7.69	[illegible]	12.90	[illegible]	9.57		10.32
Fatigue	[illegible]	34.62	[illegible]	34.95	[illegible]	23.40		30.56
Fever	[illegible]	13.85	[illegible]	20.43	[illegible]	15.43		16.87
Skin rash	[illegible]	10.00	[illegible]	15.59	[illegible]	6.38		10.71
Drowsiness	[illegible]	25.38	[illegible]	27.42	[illegible]	18.62		23.61
[illegible]								
Yes	[illegible]	42.31	[illegible]	51.61	[illegible]	39.89		44.84
No	[illegible]	40.00	[illegible]	0.00	[illegible]	34.57		23.21
[illegible]								
Daily	[illegible]	6.15	[illegible]	5.38	[illegible]	11.17		7.74
Weekly	[illegible]	23.85	[illegible]	12.90	[illegible]	28.19		21.43
Twice a week	[illegible]	20.00	[illegible]	23.12	[illegible]	22.34		22.02
Once a month	[illegible]	30.77	[illegible]	34.41	[illegible]	21.81		28.77
[illegible]								
Summer	[illegible]	47.69	[illegible]	32.26	[illegible]	38.83		38.69
Winter	[illegible]	23.08	[illegible]	23.66	[illegible]	14.89		20.24
Morning	[illegible]	25.38	[illegible]	12.90	[illegible]	15.96		17.26
Evening	[illegible]	23.08	[illegible]	25.27	[illegible]	28.19		25.79

Questions to Building Occupants	New Office Buildings		[illegible]		Comparison Buildings		[illegible]	
	[illegible]	Percentage (%)	[illegible]	Percentage (%)	[illegible]	Percentage (%)	[illegible]	Percentage (%)
[illegible]								
During morning hours	[illegible]	33.08	[illegible]	18.28	[illegible]	29.79		26.39
During afternoon hours	[illegible]	39.23	[illegible]	38.17	[illegible]	37.23		38.10
All day	[illegible]	10.00	[illegible]	15.05	[illegible]	18.62		15.08
All the time	[illegible]	3.08	[illegible]	2.69	[illegible]	4.26		3.37
[illegible]								
Asthma	[illegible]	0.77	[illegible]	5.38	[illegible]	9.57		5.75
Allergies	[illegible]	13.08	[illegible]	20.97	[illegible]	27.66		21.43
Hay fever	[illegible]	2.31	[illegible]	0.00	[illegible]	4.79		2.38
Migraines	[illegible]	2.31	[illegible]	3.23	[illegible]	13.83		6.94
Others	[illegible]	13.85	[illegible]	12.90	[illegible]	17.55		14.88
[illegible]								
Unbearable	[illegible]	0.00	[illegible]	0.00	[illegible]	2.66		0.99
Uncomfortable	[illegible]	3.08	[illegible]	15.59	[illegible]	18.09		13.29
Comfortable	[illegible]	96.92	[illegible]	82.80	[illegible]	78.72		84.92
[illegible]								
Better	[illegible]	41.54	[illegible]	53.23	[illegible]	55.32		50.99
Same as before	[illegible]	55.38	[illegible]	45.70	[illegible]	43.09		47.22
Worse	[illegible]	0.77	[illegible]	0.54	[illegible]	0.00		0.40
[illegible]								
[illegible]								
Cold	[illegible]	6.15	[illegible]	17.20	[illegible]	6.91		10.52
Slightly Cool	[illegible]	13.08	[illegible]	23.66	[illegible]	22.87		20.63
Comfortable	[illegible]	79.23	[illegible]	49.46	[illegible]	53.72		58.73
Slightly Warm	[illegible]	1.54	[illegible]	5.38	[illegible]	11.70		6.75
Hot	[illegible]	1.54	[illegible]	4.30	[illegible]	1.06		2.38
[illegible]								
Too dry	[illegible]	0.00	[illegible]	0.00	[illegible]	0.53		0.20
Dry	[illegible]	8.46	[illegible]	20.97	[illegible]	12.23		14.48
Comfortable	[illegible]	82.31	[illegible]	62.37	[illegible]	72.34		71.23
Humid	[illegible]	9.23	[illegible]	15.59	[illegible]	9.57		11.71
Too humid	[illegible]	1.54	[illegible]	0.00	[illegible]	1.06		0.79
[illegible]								
Too noisy	[illegible]	1.54	[illegible]	4.30	[illegible]	5.32		3.97
Noisy	[illegible]	10.77	[illegible]	28.49	[illegible]	25.00		22.62
Quite	[illegible]	87.69	[illegible]	68.28	[illegible]	69.68		73.81
[illegible]								
Low	[illegible]	3.85	[illegible]	10.22	[illegible]	4.79		6.55
Satisfactory	[illegible]	95.38	[illegible]	88.71	[illegible]	86.17		89.48
Intense	[illegible]	0.77	[illegible]	1.08	[illegible]	8.51		3.77
[illegible]								
Dirty	[illegible]	3.08	[illegible]	1.61	[illegible]	4.79		3.17
Smoky	[illegible]	3.08	[illegible]	2.15	[illegible]	13.30		6.55
Clean	[illegible]	92.31	[illegible]	96.24	[illegible]	81.91		89.88
[illegible]								
Still	[illegible]	29.23	[illegible]	19.89	[illegible]	44.15		31.35
Moderate	[illegible]	68.46	[illegible]	76.34	[illegible]	52.13		65.28
Drafty	[illegible]	2.31	[illegible]	4.30	[illegible]	4.26		3.77

Questions to Building Occupants	[illegible]	Percentage (%)	[illegible]	Percentage (%)	[illegible]	Percentage (%)	[illegible]	Percentage (%)
[illegible]								
6 months	[illegible]	8.46	[illegible]	1.61	[illegible]	3.19	[illegible]	3.97
9 months	[illegible]	20.00	[illegible]	22.58	[illegible]	19.15	[illegible]	20.63
12 months	[illegible]	66.15	[illegible]	74.19	[illegible]	76.06	[illegible]	72.82
[illegible]								
Too noisy	[illegible]	0.00	[illegible]	16.13	[illegible]	9.04	[illegible]	9.33
Bad smell	[illegible]	5.38	[illegible]	9.68	[illegible]	10.64	[illegible]	8.93
Too hot or cold	[illegible]	28.46	[illegible]	35.48	[illegible]	24.47	[illegible]	29.56
Too much air	[illegible]	6.92	[illegible]	7.53	[illegible]	7.98	[illegible]	7.54
Others	[illegible]	9.23	[illegible]	10.75	[illegible]	13.30	[illegible]	11.31
[illegible]								
6 months	[illegible]	13.85	[illegible]	30.11	[illegible]	34.57	[illegible]	27.58
9 months	[illegible]	6.15	[illegible]	7.53	[illegible]	12.77	[illegible]	9.13
Yearly	[illegible]	46.92	[illegible]	37.63	[illegible]	42.55	[illegible]	41.87
2 years	[illegible]	9.23	[illegible]	7.53	[illegible]	3.19	[illegible]	6.35
[illegible]								
None	[illegible]	51.54	[illegible]	41.40	[illegible]	31.38	[illegible]	40.28
Slight	[illegible]	24.62	[illegible]	28.49	[illegible]	29.79	[illegible]	27.98
Moderate	[illegible]	20.00	[illegible]	23.12	[illegible]	31.91	[illegible]	25.60
Strong	[illegible]	2.31	[illegible]	2.15	[illegible]	4.79	[illegible]	3.17
[illegible]								
Cigarette	[illegible]	32.31	[illegible]	25.27	[illegible]	47.87	[illegible]	35.52
Car exhaust	[illegible]	1.54	[illegible]	4.84	[illegible]	4.79	[illegible]	3.97
Carpet	[illegible]	6.92	[illegible]	5.91	[illegible]	3.19	[illegible]	5.16
Toilet	[illegible]	13.85	[illegible]	22.04	[illegible]	12.23	[illegible]	16.27
Furniture	[illegible]	6.92	[illegible]	6.99	[illegible]	2.13	[illegible]	5.16
Others	[illegible]	3.85	[illegible]	4.84	[illegible]	10.64	[illegible]	6.75
[illegible]								
Yes	[illegible]	34.62	[illegible]	30.65	[illegible]	51.06	[illegible]	39.29
No	[illegible]	65.38	[illegible]	67.74	[illegible]	48.94	[illegible]	60.12
[illegible]								
Yes	[illegible]	60.00	[illegible]	66.13	[illegible]	58.51	[illegible]	61.71
No	[illegible]	37.69	[illegible]	32.80	[illegible]	42.55	[illegible]	37.70
[illegible]								
Twice daily	[illegible]	12.31	[illegible]	5.38	[illegible]	44.68	[illegible]	21.83
Once daily	[illegible]	40.77	[illegible]	36.02	[illegible]	36.17	[illegible]	37.30
Once in two days	[illegible]	20.00	[illegible]	16.13	[illegible]	9.04	[illegible]	14.48
Twice a week	[illegible]	14.62	[illegible]	12.90	[illegible]	6.38	[illegible]	10.91
Once in a week	[illegible]	9.23	[illegible]	26.88	[illegible]	1.60	[illegible]	12.90

Appendix H

Building Assessment Data

		New Office Buildings	Old Office Buildings	[illegible]	Total (24)	[illegible]		New Office Buildings	Old Office Buildings	[illegible]	Total (24)	[illegible]		New Office Buildings	Old Office Buildings	[illegible]	Total (24)	[illegible]	
[illegible]	Noticeable odor	[illegible]	3		13	[illegible]	None	[illegible]	5		11	[illegible]	Moderate	[illegible]	0		0	[illegible]	Strong
	Temperature	[illegible]	2		2	[illegible]	Cold	[illegible]	6		21	[illegible]	Comfortable	[illegible]	0		1	[illegible]	Warm
	Humidity	[illegible]	0		0	[illegible]	Dry	[illegible]	8		22	[illegible]	Comfortable	[illegible]	0		2	[illegible]	Humid
	Lighting level	[illegible]	0		1	[illegible]	Low	[illegible]	8		23	[illegible]	Satisfactory	[illegible]	0		0	[illegible]	High
	Vibration and noise level	[illegible]	3		11	[illegible]	Low	[illegible]	5		13	[illegible]	Satisfactory	[illegible]	0		0	[illegible]	High
	Dirt	[illegible]	3		3	[illegible]	Yes	[illegible]	5		21	[illegible]	No						
	Smoking	[illegible]	7		20	[illegible]	Yes	[illegible]	1		4	[illegible]	No						
	Noticeable flow of air	[illegible]	1		1	[illegible]	Yes	[illegible]	7		23	[illegible]	No						
	Dampness	[illegible]	0		0	[illegible]	Yes	[illegible]	8		24	[illegible]	No						
[illegible]	Proper layout for air distribution	[illegible]	8		24	[illegible]	Yes	[illegible]	0		0	[illegible]	No						
	Return air plenum	[illegible]	8		22	[illegible]	Yes	[illegible]	0		2	[illegible]	No						
	Duct lining	[illegible]	0		0	[illegible]	Inside	[illegible]	8		24	[illegible]	Outside						
	Microbial growth in ductworks	[illegible]	0		0	[illegible]	Yes	[illegible]	8		24	[illegible]	No						
	Access doors available	[illegible]	8		24	[illegible]	Yes	[illegible]	0		0	[illegible]	No						
[illegible]	Drain pans trapped properly	[illegible]	8		24	[illegible]	Yes	[illegible]	0		0	[illegible]	No						
	Condensation problem	[illegible]	0		0	[illegible]	Yes	[illegible]	8		24	[illegible]	No						
	Evidence of water leakage	[illegible]	1		1	[illegible]	Yes	[illegible]	7		23	[illegible]	No						
	Mold growth in condensate pans	[illegible]	0		0	[illegible]	Yes	[illegible]	8		24	[illegible]	No						
	Corrosion problem	[illegible]	1		1	[illegible]	Yes	[illegible]	7		23	[illegible]	No						
	Inspection access available	[illegible]	8		24	[illegible]	Yes	[illegible]	0		0	[illegible]	No						
[illegible]	Filter type	[illegible]	8		24	[illegible]	Media	[illegible]	0		0	[illegible]	HEPA						
	Condition of filter	[illegible]	0		9	[illegible]	Excellent	[illegible]	6		13	[illegible]	Good	[illegible]	2		2	[illegible]	Bad
	Moisture buildup	[illegible]	0		0	[illegible]	Yes	[illegible]	8		24	[illegible]	No						
	Filter location	[illegible]	8		24	[illegible]	Before	[illegible]	0		0	[illegible]	After						
	Frequency of cleaning	[illegible]	0		3	[illegible]	Twice	[illegible]	0		13	[illegible]	Thrice	[illegible]	4		4	[illegible]	6-12 month
	Inspection access available	[illegible]	8		24	[illegible]	Yes	[illegible]	0		0	[illegible]	No						
[illegible]	Fresh air intake	[illegible]	6		22	[illegible]	Yes	[illegible]	2		2	[illegible]	No						
	Bird screen obstructed	[illegible]	0		0	[illegible]	Yes	[illegible]	7		23	[illegible]	No						
	Parking facility or road nearby	[illegible]	7		20	[illegible]	Yes	[illegible]	1		4	[illegible]	No						
	Exhaust outlet within 25 feet	[illegible]	1		5	[illegible]	Yes	[illegible]	7		19	[illegible]	No						
[illegible]	Central exhaust system	[illegible]	2		9	[illegible]	Yes	[illegible]	6		15	[illegible]	No						
	Separate smoking areas w/exhaust	[illegible]	0		0	[illegible]	Yes	[illegible]	8		24	[illegible]	No						
	Doors to building close tightly	[illegible]	7		23	[illegible]	Yes	[illegible]	1		1	[illegible]	No						
	Mechanical room conditions	[illegible]	0		7	[illegible]	Excellent	[illegible]	3		12	[illegible]	Good	[illegible]	5			[illegible]	Bad
	Controls are operational	[illegible]	8		24	[illegible]	Yes	[illegible]	0		0	[illegible]	No						
	Maintenance/inspection schedule	[illegible]	3		16	[illegible]	Yes	[illegible]	5		8	[illegible]	No						
	Contaminant generation areas	[illegible]	8		21	[illegible]	Yes	[illegible]	0		3	[illegible]	No						

REFERENCES

1. Al-Rehaili, A. M., Al-Mutaz, I. S. and Al-Megren K. A. (1997). "Investigation of Indoor Air Pollution in Riyadh", **Research Project**, No. AR-12-48, King Saud University, Riyadh.

2. Al-Qahtani, A. S. (1993). "Subjective Assessment Of Indoor Air Quality In Office Buildings", **M. S. Thesis**, King Fahd University of Petroleum and Minerals, Dhahran.

3. Al-Zahamah, I. T. (1996). "Quantitative And Subjective Assessments Of Indoor Air Quality In KFUPM Buildings", **M. S. Thesis**, King Fahd University of Petroleum and Minerals, Dhahran.

4. Angevine, E. N. and Fair, J. S. (1995). "HVAC Systems", **Energy Management Handbook**, pp. 245-270.

5. ASHRAE (1989a). "Ventilation For Acceptable Indoor Air Quality", **ANSI/ASHRAE Standard 62-1989**, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, Georgia.

6. ASHRAE (1989b). "Guideline For Commissioning Of HVAC Systems". **Guideline GPCI-1989**, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, Georgia.

7. ASHRAE (1992). "Thermal Environmental Conditions for Human Occupancy", **ANSI/ASHRAE Standard 55-1992**, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, Georgia.

8. ASHRAE Handbook (1995). **HVAC Applications**, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, Georgia.

9. ASHRAE Handbook (1996). **HVAC Systems and Equipment**, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, Georgia.

10. ASHRAE Handbook (1997). **Fundamentals**, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, Georgia.

11. ASHRAE Insights. (1998). The **Newspaper** of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., September, Vol. 13, No. 9.

12. Batterman, S. A. and Burge, H. (1995). "HVAC As Emission Sources Affecting Indoor Air Quality: A Critical Review", **HVAC&R Research**, January, Vol. 1, No. 1, pp. 61-80.

13. Bayer, C. W. and Black, M. S. (1988). "IAQ Evaluations Of Three Office Buildings", **ASHRAE Journal**, July, Vol. 30, No. 7, pp. 48-53.

14. Berglund, L. G. (1998). "Comfort and Humidity", **ASHRAE Journal**, August, Vol. 40, No. 8, pp. 35-41.

15. Budaiwi, I. M. (1998). "Impact of Combined Dilution and Pressurization Effects of Ventilation Air on Indoor Contaminant Concentration", **Indoor Built Environment**, Vol. 7, No. 5-6, pp. 289-299.

16. Burge, H. A. and Hodgson, M. (1988). "Health Risks Of Indoor Pollutants", **ASHRAE Journal**, July, Vol. 30, No. 7, pp. 34-38.

17. Burroughs, H. E. (1997a). "IAQ: An Environmental Factor In The Indoor Habitat", **HPAC Journal**, February, Vol. 69, No. 2, pp. 57-60.

18. Burroughs, H. E. (1997b). "Filtration: An Investment in IAQ", **HPAC Journal**, August, Vol. 69, No. 8, pp. 55-65.

19. Cain, W. S., Samet, J. M. and Hodgson, M. (1995). "The Quest For Negligible Health Risk From Indoor Air", **ASHRAE Journal**, July, Vol. 37, No. 7, pp. 38-44.

20. Collett, C. W., Ross, J. A. and Sterling, E. M. (1993). "Strategies For The Investigation Of Indoor Air Quality Problems And Findings From Their Implementation", **ASHRAE Transactions**, Vol. 99, Part 2, pp. 1104-1110.

21. Croome, D. J., Gan, G. and Awbi, H. B. (1992). "Evaluation Of Thermal Comfort And Indoor Air Quality In Offices", **Building Research and Information**, Vol. 20, No. 4, pp. 211-225.

22. Davis, J. R. (1998). "Avoiding Litigation Arising From IAQ Complaints", **Indoor Air**, October, Vol. 70, No. 10, pp. 89-92.

23. Donnini, G., Molina, J., Martello, C., Lai, D. H. C., Lai, H. K., Chang, C. Y., Laflamme, M, Nguyen, V. H., Haghighat, F. (1997). **ASHRAE Transactions**, Vol. 103, No. 2, pp. 205-220.

24. Downing, C. C. and Bayer, C. W. (1993). "Classroom Indoor Air Quality Vs. Ventilation Rate", **ASHRAE Transactions**, Vol. 99, Part 2, pp. 1099-1103.

25. EPA (1998). "Building Air Quality Action Plan", **EPA Publication No. 402-K-98-001**, U.S. Environmental Protection Agency, June.

26. Fang, L., Clausen, G. and Fanger, P. O. (1998). "Impact Of Temperature And Humidity On The Perception Of Indoor Air Quality", **Indoor Air**, June, Vol. 8, No. 2, pp. 80-90.

27. Fanger, P. O. (1998). "Discomfort Caused By Odorants And Irritants In The Air", **Indoor Air**, Vol. 8, No. 4, pp. 81-86.

28. Filardo Jr., M. J. (1993). "Outdoor Air: How Much Is Enough?". ASHRAE **Journal**, January, Vol. 35, No. 1, pp. 34.

29. Fink, J. N. (1998). "Humidifier Fever, Contaminated HVAC And Hypersensitivity Pneumonitis", **Indoor Air**, September, Vol. 8, No. 3, pp. 56-58.

30. Gan, G. and Croome, D. J. (1994). "Thermal Comfort Models Based on Field Measurements", **ASHRAE Transactions**, Vol. 100, No. 1, pp. 782-794.

31. Gardner, T. F. (1990). "Is The Ventilation Engineer Responsible For Sick Building Syndrome Damages?", **ASHRAE Journal**, August, Vol. 32, no. 8, pp. 22-25.

32. Godish, T. (1995). **Sick Buildings: Definition, Diagnosis and Mitigation.** Lewis Scientific Publishers, Ann Arbor, MI.

33. Grot, R. A., Hodgson, A. T., Daisey, J. M., and Persily, A. (1991). "Indoor Air Quality Evaluation of a New Office Building", **ASHRAE Journal**. September. Vol. 33, no. 9, pp. 16-25.

34. Haghighat, F. and de Bellis, Lisa. (1998). "Material Emission Rates: Literature Review, and the Impact of Indoor Air Temperature and Relative Humidity", **Building and Environment**, September, Vol. 33, No. 5, pp. 261-277.

35. Haghighat, F. and Donnini, G. (1999). "Impact of Psycho-social Factors on Perception of the Indoor Air Environment Studies in 12 Office Buildings", **Building and Environment**, July, Vol. 34, No. 4, pp. 479-503.

36. Hansen, S. J. (1991). **Managing Indoor Air Quality**, The Fairmont Press, Inc., Lilburn.

37. Hays, S. M., Gobbell, R. V. and Ganick, N. R. (1995). **Indoor Air Quality: Solutions and Strategies**, McGraw-Hill, Inc., New York.

38. Hodgson, M. J. and Hess, C. A. (1992). "Doctors, Lawyers and Building Associated Diseases", **ASHRAE Journal**, February, Vol. 34, No. 2, pp. 25-32.

39. Howell, R. H., Sauer, Jr. H. J. and Coad, W. J. (1998). **Principles of Heating, Ventilating, and Air-Conditioning**, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Inc., Atlanta, Georgia.

40. Int-Hout, D. (1993). "Total Environmental Quality", **ASHRAE Transactions**, Vol. 99, Part 1, pp. 960-967.

41. Kennedy, C. R. and Al Distefano (1991). " Improving Building IAQ Reduces HVAC Energy Costs", **HPAC Journal**, November, Vol. 30, No. 7, pp. 75-79.

42. Lahtinen, M., Huuhtanen, P. and Reijula, K. (1998). "Sick Building Syndrome And Psychosocial Factors – A Literature Review", **Indoor Air**, Vol. 8, No. 4, pp. 71-80.

43. McQuiston, F. C. and Parker, J. D. (1994). **Heating, Ventilating, and Air Conditioning: Analysis and Design**, John Wiley & Sons, Inc., New York.

44. Meckler, M. (1991). "Indoor Air Quality From Commissioning Through Building Operations", **ASHRAE Journal**, November, Vol. 33, No. 11, pp. 42-48.

45. Meckler, M. (1996). **Improving Indoor Air Quality Through Design, Operation and Maintenance**, The Fairmont Press, Inc., Lilburn.

46. Namiesnik, J., Gorecki, T., Zabiegala, B. K. and Lukasiak, J. (1992). "Indoor Air Quality, Pollutants, Their Sources And Concentration Levels", **Building and Environment**, Vol. 27, No. 3, pp. 339-356.

47. Naumann, K. and Lamecker, D. (1998). "Responding To Indoor Air Quality Problems", **Indoor Air**, June, Vol. 8, No. 2, pp. 80-90.

48. O'Sullivan, P. (1989). "Energy And IAQ Can Be Complementary", **HPAC Journal**, February, pp. 37-42.

49. Ohman, P. A. and Eberly, L. E. (1998). "Relating Sick Building Syndrome To Environmental Conditions And Worker Characteristics", **Indoor Air**, June, Vol. 8, No. 2, pp. 172-179.

50. Poruthoor, S. K., Dasgupta, P. K. and Genfa, Z. (1998). "Indoor Air Pollution and Sick Building Syndrome. Monitoring Aerosol Protein As A Measure Of Bioaerosols", **Environment Science & Technology**, Vol. 32, No. 8, pp. 1147-1152.

51. Schultz, K. J. and Krafthefer, B. C. (1993). "CO_2-Based Ventilation Control: Choice Of CO_2 Setpoint", **ASHRAE Transactions**, Vol. 99, Part 1, pp. 1548-1553.

52. Scofield, C. M. and Champs, N. H. (1995). "Low Temperature Air With High IAQ For Dry Climates", **ASHRAE Journal**, January, Vol. 37, No. 1, pp. 34-40.

53. Singh, J. (1993). "Biological Contaminants In The Built Environment And Their Health Implications", **Building Research and Information**, Vol. 21, No. 4, pp. 216-224.

54. Sparks, L. E. (1988). "Air Cleaners And Indoor Air Quality", **ASHRAE Journal**, July, Vol. 30, No. 7, pp. 45.

55. Stanke, D. (1999). "Ventilation Through the Years: A Perspective". **ASHRAE Journal**, August, Vol. 41, No. 8, pp. 40-43.

56. Stein, B. and Reynolds, J. S. (1992). **Mechanical And Electrical Equipment For Buildings**, John Wiley & Sons, Inc., NewYork.

57. Sterling, E., Collett, C., Turner, S. and Downing, C. (1993). "Commissioning To Avoid Indoor Air Quality Problems", **ASHRAE Transactions**, Vol. 99, Part 1, pp. 867-870.

58. Sterling, E., Collett, C. and Ross, J. A. (1996). "Dilution Ventilation To Accommodate Smoking: A Case Study", **HPAC Journal**, November, Vol. 68, No. 11, pp. 81-88.

59. Stonier, R. T. (1995). "CO_2: Powerful IAQ Diagnostic Tool", **HPAC Journal**, March, Vol. 67, No. 3, pp. 88-90.

60. Tamblyn, B. T. (1992). "Commissioning: An Operation And Maintenance Perspective", **ASHRAE Journal**, October, Vol. 34, No. 10, pp. 22-26.

61. Taylor, S. T. (1990). "HVAC Systems And Equipment: An Overview of Standard 90.1", **ASHRAE Journal**, February, Vol. 32, No. 2, pp. 26-35.

62. Thompson, B. (1998). "Engineers, IAQ, and Schools", **ASHRAE Journal**, Insert, June, Vol. 40, No. 6, pp. 22-26.

63. Ventresca, J. A. (1995). "Ventilation System O&M: A First Step For Improving IAQ", **ASHRAE Journal**, January, Vol. 37, No. 1, pp. 19-23.

64. Vischer, J. C. (1993). "Using Occupant's Experiences To Monitor Indoor Air Quality In Office Buildings", **ASHRAE Transactions**, Vol. 99, Part 21, pp. 1111-1115.

65. Wadden, R. A. and Scheff, P. A. (1983). **Indoor Air Pollution**, John Wiley & Sons, New York.

66. Wendl, D. (1996). "Strategic Direction for the IAQ Industry", **Energy Engineering**, Vol. 93, No. 6, pp. 64-78.

67. Wenger, J. D. (1997). "Monitoring Technology For Improved Indoor Air Quality", **AFE Facilities Engineering**, March/April, pp. 13-15.

68. Wheeler, A. E. (1988). "Office Building Air Conditioning To Meet Proposed ASHRAE Standard 62-1981R", **ASHRAE Journal**, July, Vol. 30, No. 7, pp. 40-43.

69. Wheeler, A. E. (1992). "Energy Conservation And Acceptable Indoor Air Quality In The Classroom", **ASHRAE Journal**, April, Vol. 34, No. 4, pp. 26-32.

70. Wilkinson, R. J. (1999). "The Commissioning Design Intent Narrative", **ASHRAE Journal**, April, Vol. 41, No. 4, pp. 31-35.

VITA

- ***Raza Ahmed Khan***
- Born on 19th June 1973, in Hyderabad, India.
- Address:

  H.No. 16-1-14/5, Dr. Zakir Hussain Colony,
  Saidabad, Hyderabad 500 059, India.

  E-mail: raza_a_khan@hotmail.com
- Received Bachelor of Engineering (B.E.) degree in ***Mechanical Engineering*** from Osmania University, Hyderabad, India in June 1994.
- Received Master of Science (M.S.) degree in ***Architectural Engineering*** from King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia in June 2000.